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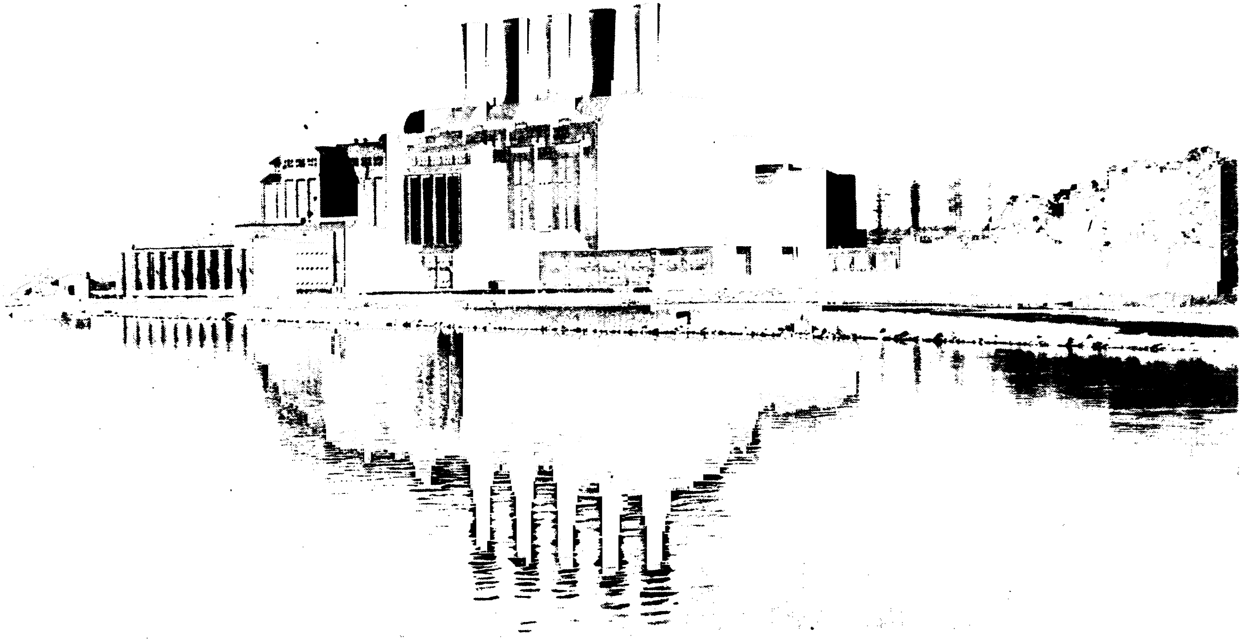

A LARGE MODERN POWER PLANT

THE AMERICAN ELECTRICIAN SERIES

Practical and Technical Electricity

POWER WIRING
(ALTERNATING CURRENT)

BY

JOSEPH G. WOLBER, A. M.
Formerly Head of the Mechanical Arts Courses, Cass Technical High School
now Assistant Principal, Northwestern High School and
Principal of the Evening School

AND

OTTO K. ROSE, A. M.
Head of the Electrical Department Cass Technical High School

CHICAGO
THE GOODHEART-WILLCOX COMPANY, INC.
Publishers
1937

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Printed in the United States of America

PREFACE

This volume is the third of a series on electrical circuits and machinery for light and power. The preceding volumes present the subjects of Wiring and of Direct Current Circuits and Machinery. This volume discusses Alternating Current Circuits and Machinery.

Like the preceding volumes, this book is intended not only for school use, but also for the average electrical man who wants technical explanations of the behavior of electrical circuits and equipment.

The manner in which the previous volumes have been received and the numerous requests to the publishers concerning the present volume have been sources of great encouragement to the authors.

We wish to thank the many manufacturing concerns without whose help in furnishing cuts and illustrative material, as well as data, this book would not have been possible.

JOSEPH G. WOLBER
OTTO K. ROSE

DETROIT, MICHIGAN
October 1, 1937

INTRODUCTION

Certain features of this book call for an explanation. These are: a chapter on mathematics; the discussion of motors previous to alternators and transformers, which is unusual; the large amount of space devoted to motor controls.

Concerning the first point, mathematics, it may be argued that this chapter is not essential for technical high-school boys since it is customary to give such boys a thorough course in mathematics. This is only partly true, however, because often the study of electricity precedes certain parts of the mathematics course, which is necessary, and also because such topics as vectors and vector addition are not taught in mathematics classes at all. Further, a bird's-eye view, such as is given in Chapter I, will be of benefit to students even if they have had a good mathematics preparation. For most evening-school pupils, Chapter I is a real blessing.

The presentation of the motor topics before the discussion on alternators is not at all serious. By far the largest number of evening-school pupils are much more interested in a study of motors than in the alternator. Moreover, the basic principle of the alternator is actually discussed in Chapters II and III in connection with circuits so that the difficulty suggested above is more imaginary than real. This method of procedure also allows a generous discussion of the central station, in the chapter on alternators. Students are ready for laboratory assignments on motors earlier in the course, and this makes the dovetailing of recitation with laboratory very convenient.

A fairly thorough discussion of controls is essential in a book on alternating current circuits and machinery. Controls are often mysterious to the electrical man. While he may have learned to move a lever or press a button, or make the connection according to a wiring diagram pasted on the inside cover of a piece of equipment, he longs to know what goes on inside. The purpose of going into detail is to enable the electrical man to become a more intelligent worker in his field.

TABLE OF CONTENTS

TABLE OF CONTENTS

CHAPTER PAGE

I. MATHEMATICS FOR ELECTRICAL STUDENTS . . . 1

Mathematics Essentials—Plotting Graphs—Some Valuable Geometric Ideas—Ratio—Proportion—Sine—Cosine—Sine and Cosine Tables—Use of Sine and Cosine—Graphical Solutions—Vectors—Problems.

II. VOLTAGE, CURRENT, IMPEDANCE 25

Alternating Voltage—Alternating Current—Frequency—Alternating vs. Direct Current—Resistance—Alternating Volts, Amperes, Ohms—Inductance—Reactance—Inductive Reactance—Capacity Reactance—Action of Condenser—In Phase—Out of Phase—Impedance—Impedance Triangle—Problems.

III. OHM'S LAW, POWER 66

Ohm's Law for A. C. Circuits—Solution of Series and Parallel Circuits—Power—Power Equation—Power Factor—Kilowatts—Kilowatt-hours—Kilovolt-amperes—Problems.

IV. POLYPHASE CIRCUITS 93

Single Phase Circuit—Two-Phase Circuit—Two-Phase Three-Wire Circuit—Other Two-Phase Arrangements—Two-Phase Load Connections—Choice of Polyphase Systems—Three-Phase Star—Three-Phase Delta—Three-Phase Voltage Relations—Three-Phase Current Relations—Unbalanced Three-Phase Circuits—Power in Three-Phase Circuits—Three-Phase Open Delta—Problems.

V. ALTERNATING CURRENT METERS 136

Classification of Meters—Essential Parts—Electrodynamometer Type—Electromagnet Type—Hot Wire Instruments—Watthour Meter—Demand and Prepayment Meters—Instrument Transformer—Synchroscope—Power Factor Meter—Frequency Meter—Pyrometers

TABLE OF CONTENTS

CHAPTER PAGE

VI. SINGLE PHASE MOTORS 185

Kinds—Shaded-Pole Motor—Split-Phase Motor—Condenser-Type Motor—Repulsion-Type Motor—Modifications of Repulsion Motor—Series Motor—Synchronous Speed—Slip—Torque—Single-Phase Motor Characteristics—Problems.

VII. THREE-PHASE MOTORS 239

Stator Construction—Stator Winding—Rotor Construction—Revolving Field—Cause of Rotation—Slip—Speed Control—Three-Phase Motor Characteristics—Fynn-Weichsel Motor—Problems.

VIII. A. C. MOTOR STARTING DEVICES 298

National Code—Local Regulations—Single-Phase Starters—Three-Phase Starters—Compensators—Speed Regulators—Magnetic Switches—Automatic Starters—Overload Protection—Undervoltage Protection.

IX. ALTERNATORS 335

Central Stations—Station Efficiency, Power Factor, Cost of Production—Alternator Construction—Laboratory Alternator—Alternator Field Excitation—Voltage Regulation—Armature Reaction—Parallel Operation—Synchronizing—Load Equalization—Synchronous Condenser—Problems.

X. TRANSFORMERS 372

Transformer Principle—Construction—Cooling—Polarity—Connections—Transformation from Three- to Six-Phase—Transformation from Two- to Three-Phase—Auto-transformer—Voltage regulation—Vector Diagrams—Efficiency—Special Duty Transformer—Rotary Converter—Problems.

XI. ELECTRIC POWER DISTRIBUTION 425

Transmission—Underground—Overhead—Transmission Voltages—Sub-stations—Consumer Voltages.

APPENDIX 449

INDEX 457

CHAPTER I

MATHEMATICS FOR ELECTRICAL STUDENTS

1. MATHEMATICS ESSENTIALS:

The need for some form of mathematics as an aid in solving electrical problems becomes apparent to the student at the very outset of his course. And as the student advances in his knowledge of the subject of electricity he finds himself called upon to use higher forms of mathematics.

What is the minimum amount of mathematical information which the student must have to complete successfully a course in electricity? For the average student in a technical high school or in an evening vocational school, this minimum may be set down perhaps as follows:

a) The fundamental operations of arithmetic: addition, subtraction, multiplication, division, common and decimal fractions, square root, etc.

b) Ability to solve simple algebraic equations involving one unknown, and also simple fractional equations with one unknown. Electrical problems can usually be solved by use of a formula.

Thus:

$$I = \frac{E}{R}$$

$$P = EI$$

$$P = I^2R$$

$$\text{H.P.} = \frac{2\pi NT}{33{,}000}$$

are examples of formulas for the solution of problems in which one of the factors is unknown.

c) A very limited knowledge of geometric definitions and facts, such as:

Equal angles, right angles, perpendiculars, parallelogram, triangle, square, rectangle, circles; the use of such formulas as $C = \pi d = 2\pi r$; the use of a protractor; the solution of the right triangle, $c^2 = a^2 + b^2$.

d) A knowledge of how to plot graphs and performance curves from experimental data.
e) An elementary knowledge of ratios and simple proportion.
f) A knowledge of how to read tables containing electrical data, specifications, or other facts. This should include also ability to read sine and cosine tables.
g) A knowledge of graphical solutions, of electrical problems, as "short cuts" sufficiently accurate for practical purposes.

The purpose of this chapter is to encourage the student who lacks mathematical training, or who has had a very limited training, and to add to his mathematical information a few facts which will be of great assistance to him especially when he undertakes the study of alternating current electricity. Accordingly, let us discuss briefly the following: the plotting of graphs, some geometric ideas, simple ratio and proportion, sine and cosine functions, sine and cosine tables, and graphical solutions.

2. PLOTTING GRAPHS:

A graph is a picture representation of a series of connected facts. It is a convenient method of presenting data of any kind in condensed form. Thus Fig. 1 illustrates a graph that shows the electrical power consumption by industrial plants in the United States between 1905 and 1925. Note that the individual years 1905, 1906, 1907, etc., are represented along the horizontal lines, while the power consumption in billions of kilowatt-hours is pictured along the vertical lines. This graph shows that the trend is toward a further increase in electrical power consumption. Note the setback or dropping off of power consumption in 1921, a year of industrial depression.

The graph illustrated in Fig. 1 is a point-to-point graph and is typical of graphs which picture the relationship between two varying quantities each of which is independent. Fig. 2 illustrates a smooth graph. It pictures the manner in which a piece of iron becomes magnetized when it is placed inside a coil of wire carrying a current of electricity. The degree of magnetization is measured by flux density, plotted along the vertical or Y-axis and the changing current in the coil is plotted along the horizontal or X-axis, in terms of magnetomotive force. The flux density depends upon the change in current. Observe that there is here a smoothly drawn graph, not a point-to-point graph.

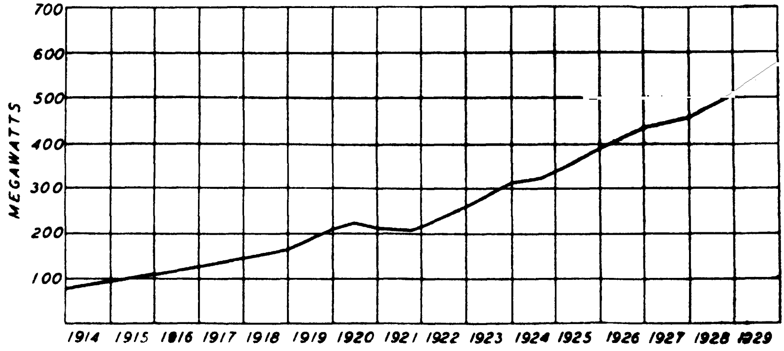


FIG. 1

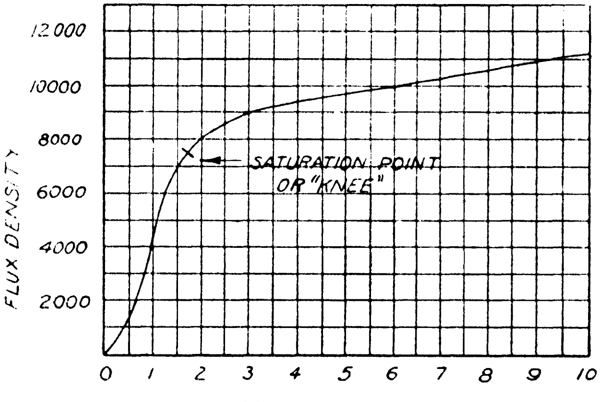


FIG. 2

Fig. 3 shows another smooth graph. Here the efficiency and the horsepower output are the two varying quantities. The efficiency of a motor changes when the load output increases or decreases. The efficiency, therefore, depends upon the output. Hence output is the independent variable, efficiency is the dependent variable. You should learn to read a graph like that

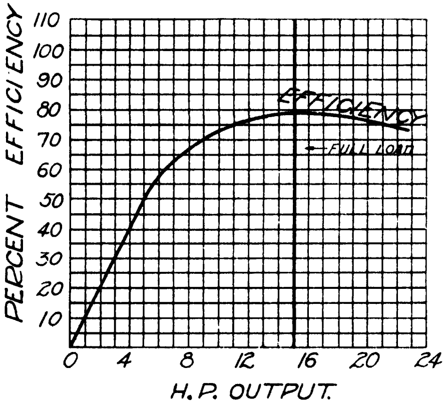


FIG. 3

in Fig. 3 somewhat as follows. The efficiency of the motor is zero when it has no output; it is low, when the output is small; it rises rapidly as the output of the motor increases, and be-

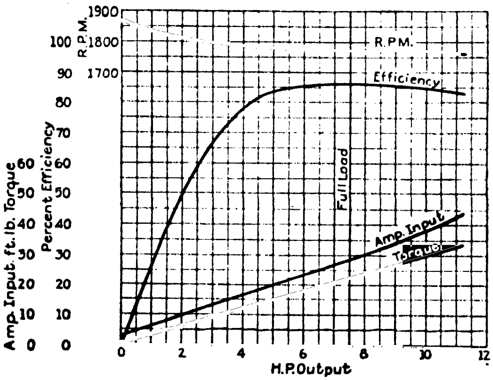


FIG. 4

comes fairly constant when the motor is 60% or more loaded; it drops when the motor is considerably overloaded.

Sometimes it is convenient to place several graphs on the same sheet even though more than one set of numbers must be used to designate the value of scale divisions along the two axes. Thus in Fig. 4 are shown several graphs, all relating to the same motor. Each graph bears its own label to identify it and the scale to be used bears the same label.

Sometimes, it is more convenient not to start the scales, both horizontal and vertical, with zero, because of waste of paper and space. Also occasionally a graph may be used which needs to show positive and negative values for both variables.

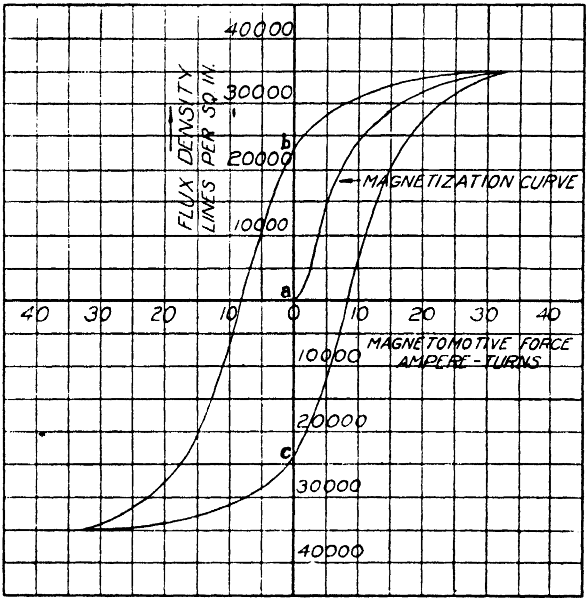


Fig. 5

Fig. 5 is an example of this. The zero is at the center of the sheet, and the four quarters or quadrants are used.

3. SOME VALUABLE GEOMETRIC IDEAS:

Let the student be certain, first of all, that he clearly understands the meaning of certain common terms and the symbols used to represent these terms. Some of these are indicated in Fig. 6.

Upon occasion the student will have need for certain geometrical facts and formulas. Some of these are reviewed here.

a) Angles are measured in degrees, minutes, and seconds. A circle comprises 360 degrees, a degree comprises 60 minutes, and each minute, 60 seconds. For our purposes degrees are sufficient. We shall have to distinguish

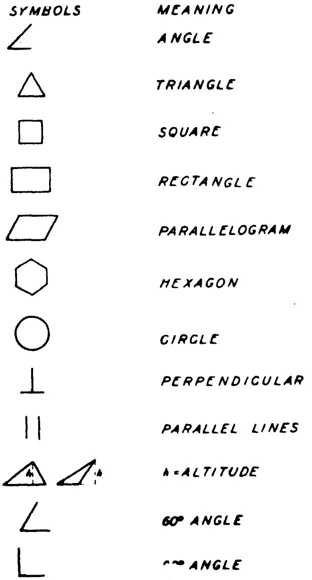


FIG. 6

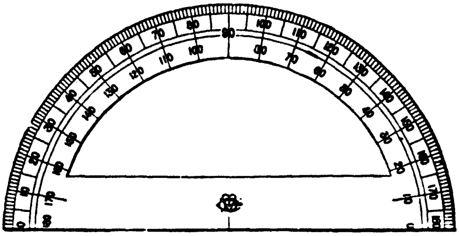


FIG. 7

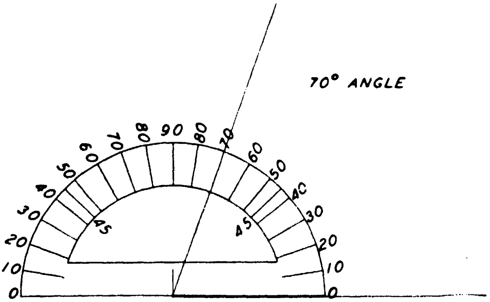


FIG. 8

later on between mechanical degrees and electrical degrees.

b) Degrees are easily and quickly determined by a protractor. See Figs. 7 and 8.

c) Fig. 9 shows two angles, A and B. They are said to be *adjacent angles.* If $A = 60°$ and $B = 30°$, the two together are equal to 90° or a right angle. If angle $A =$ 60° and angle $B = 120°$, as in Fig. 10, then the two together are equal to two right angles or 180°.

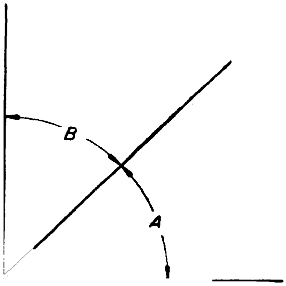


FIG. 9

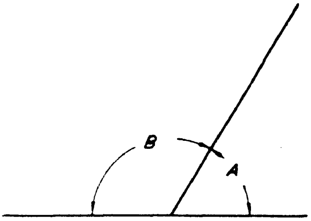


FIG. 10

d) In Fig. 11 two straight lines intersect each other at the point O. The angles A and B are equal. So, too, are angles C and D.

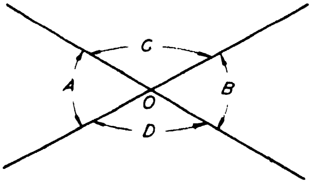


FIG. 11

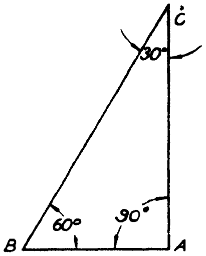


FIG. 12

e) In any triangle the three angles inside the triangle are together equal to 180° or two right angles. Thus, Fig. 12, the three angles A, B, and C, are respectively equal to 90°, 60°, and 30°, and together they equal 180°. Try this out on any triangle you may draw with a straight edge.

f) The area of a triangle is equal to the product of the base by ½ the altitude.

$$A = b \times \frac{h}{2}$$
$$= \tfrac{1}{2}bh$$

g) The area of a square is equal to the length of the side squared.

$$A = l^2$$

h) The area of a rectangle is equal to the length times the width.

$$A = l \times w$$

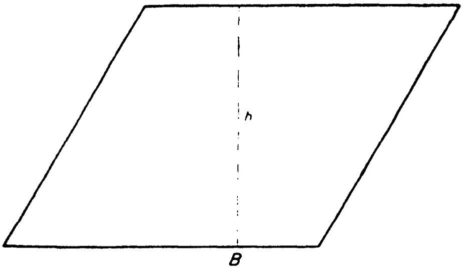


FIG. 13

i) The area of a parallelogram is equal to the base times the altitude.

j) In Fig. 14, *a* and *b* are called the diagonals of the parallelogram.

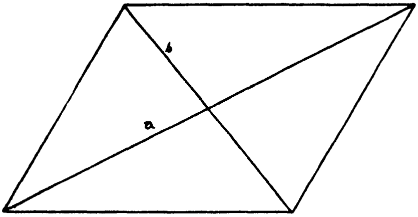


FIG. 14

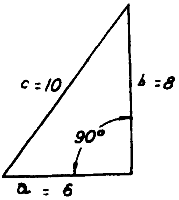


FIG. 15

k) The triangle shown in Fig. 15 is a right triangle, because one of the three angles is a 90° angle or a right angle. The three sides are 6, 8 and 10 units in length respectively. If we square these three numbers, 6 and 8 and 10, we get 36, 64, and 100. Note that the two smallest of these added together give the third. Thus,

$$100 = 36 + 64.$$

This is true of all right triangles, namely, that the sum of the squares of the two shortest sides equals the square of the longest side or hypotenuse. Or, referring again to Fig. 15, we may state that

$$10^2 = 6^2 + 8^2$$

or

$$c^2 = a^2 + b^2$$

This means that if we know two sides of a right triangle we can find the third side. The above statement can be written also

$$c^2 - b^2 = a^2$$

from which

$$\sqrt{c^2 - b^2} = a$$

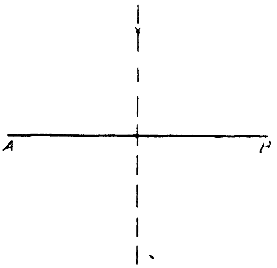


FIG 16

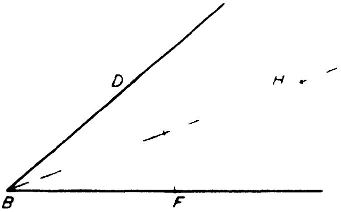


FIG 17

l) How to bisect a line *AB*. See Fig. 16.

m) How to bisect an angle *B*.

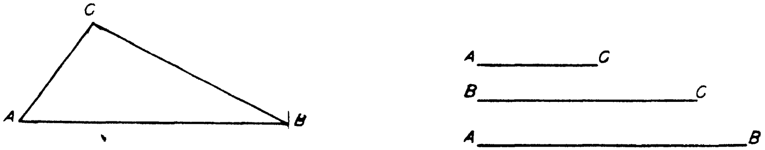


FIG 18

n) If three sides of a triangle are given, the triangle can be constructed. Suppose the three sides are 1 inch, 1½ inches, and 2 inches respectively. See Fig. 18.

o) Two formulas very frequently used by electrical students are,

$$C = 2\pi r$$
$$= \pi d$$

and $$A = \pi r^2$$

p) In any circle a line that cuts the circumference is called a chord. Thus, in Fig. 19 lines AB and CD are called chords. If O is the center of the circle then OR is a radius and so too is OM. If OR is ⊥ to the cord CD then it bisects CD also. Or if OR bisects CD it is also ⊥ to CD. Similarly for OM.

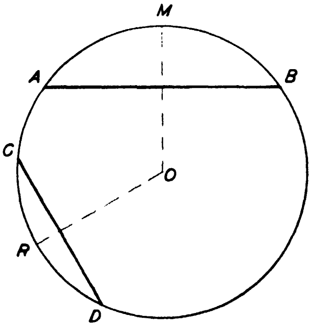


FIG. 19

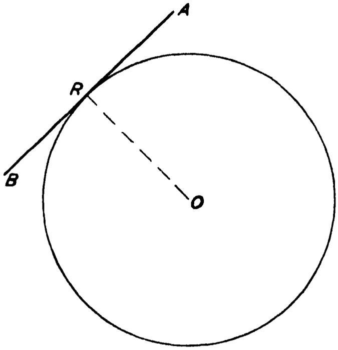


FIG. 20

q) In Fig. 20, the line AB touches the circle at a single point. AB is said to be tangent to the circle. The radius OR, is ⊥ to AB at the point at which AB is tangent.

r) The radius of any circle divides the circumference of that circle into six equal parts. Thus, Fig. 21, with OR as radius, using a compass we can divide the circle into six equal parts. If we draw chords from each point to the next, we get a six-sided figure, with equal sides, or a hexagon. This figure has a definite relation with six-phase electrical circuits.

s) In the above figure, we can skip every other point on the circumference and construct a triangle RST as shown in Fig. 22. This geometrical figure has a definite relationship with three-phase electrical circuits.

4. RATIO, PROPORTION:

If you have ten dollars and your neighbor has twenty dollars, you have ½ as much money as he. Another way of making the comparison is by saying that you have one dollar for every two dollars that he has. Ten dollars compared to twenty dollars is the same as one dollar compared to two dollars. The idea of comparison between two numbers of the same kind is the idea involved in ratio. The comparison is made as to size of numbers, and is expressed as a quotient. That is, the ratio of ten dollars to twenty dollars is found by dividing 10 by 20, so this ratio is ½.

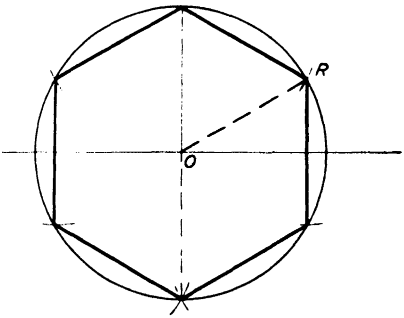


FIG. 21

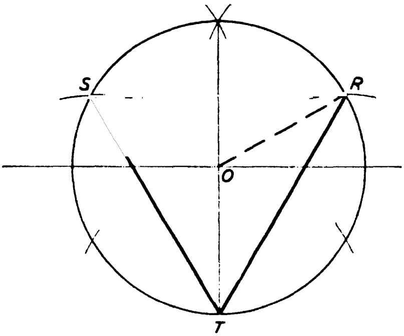


FIG. 22

If one generator develops 2,200 volts and another 220 volts, the ratio of the second voltage to the first is 10 to 1 or,

$$\frac{2200}{220} = 10$$

If the first generator delivers 500 amperes and the second generator delivers 50 amperes, then the ratio of the first current to the second is also 10 to 1, or,

$$\frac{500}{50} = 10$$

In both cases the ratios are 10 to 1. The two ratios are equal. Therefore, it is permissible to write

$$\frac{2200}{220} = \frac{500}{50}$$

and when we have done this we have merely stated that the ratio of 2,200 to 220 is the same as the ratio of 500 to 50. The above equation is called a proportion. It consists of two equal ratios set down as an equation.

Now note that in the above equation we can multiply 2,200 by 50, and 220 by 500 and in both cases we get 11,000. This is

$$\frac{2200}{220} = \frac{500}{50}$$

called cross-multiplying, and is the method used for solving a proportion when one of the numbers is not known.

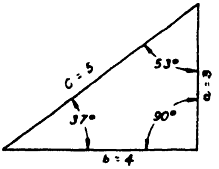


Fig. 23

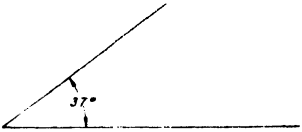


Fig. 24

5. SINE, COSINE:

Examine Fig. 23. It is a right triangle. The three sides are respectively 3, 4, and 5 units in length. The angles are 90°, 53°, and 37°. Let us draw another right triangle having the same angles, but with sides longer than in Fig. 23. For convenience let us double the length of the hypotenuse. First we construct an angle *A* equal to 37° (Fig. 24). Next we lay off the desired 10 units length for the hypotenuse, as in Fig. 25. From point *B* we now drop a perpendicular to the base of the triangle as in Fig. 25. And now we have our right triangle, *ABC*, with angles 90°, 53°, and 37° and with the hypotenuse equal to 10 units. See Fig. 26. Finally we measure the length of sides *A* and *B* and find that they are 6 and 8 units respectively. Now let us note what has happened. The angles in the two triangles, Figs. 23 and 26, are the same. The hypotenuse was doubled and this had the effect of doubling the other two sides also. In other words there is a definite relationship between the lengths of the sides of right triangles and this relationship remains the same so long as the angles remain the same, regardless of the size of the triangle. Thus in Fig. 23, side A is 3, side c is 5. Side a is three-fifths as long as side c or the ratio of side a to side $c = \frac{3}{5}$. Similarly, the ratio of side b to side $c = \frac{4}{5}$. Increasing the length of the sides as in

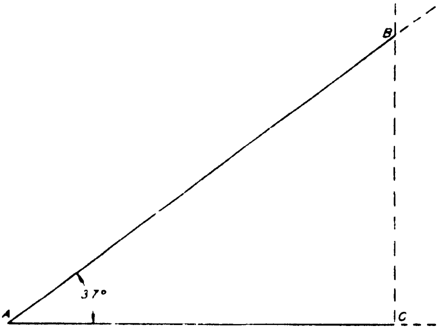


FIG. 25

Fig. 26, but keeping the angles the same, has not changed these ratios, since in Fig. 26 the ratio of side a to side $c = \frac{6}{10}$ or $\frac{3}{5}$ and the ratio of side b to side $c = \frac{8}{10}$ or $\frac{4}{5}$. Moreover these

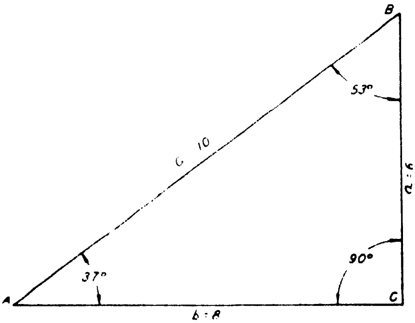


FIG. 26

ratios are the same for all right triangles whose angles are 90°, 53°, and 37°. Thus in Fig. 27, we have several triangles and the ratio of a to c in each case is $\frac{6}{10}$, the ratio of b to c is

$\frac{8}{10}$. Advantage has been taken of these facts to construct tables of ratios for right triangles, so as to make computations involving such triangles, easier. And for convenience, names have been given to the ratios between sides. Thus in Fig. 28, the ratio of side *a* to side *c* is called the sine of angle 37°. This means that in any right triangle in which one of the angles is 37°, there is a ratio between the sides that correspond to *a* and *c* equal to six-tenths. Now, note that side *a* is opposite the angle 37° and that side *c* is the hypotenuse. The ratio of the side that is opposite an angle to the hypotenuse is called the sine of that angle. Thus, Fig. 28,

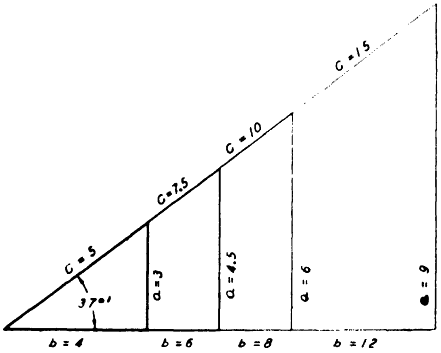


Fig. 27

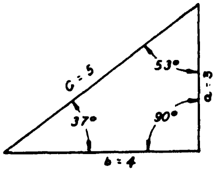


Fig. 28

$$\frac{\text{length side } a}{\text{length hypotenuse } c} = \text{sine of angle } 37^\circ$$

Again, side *b* is adjacent to the angle 37°. The ratio of side *b* to the hypotenuse is eight-tenths. The ratio of the side adjacent to an angle to the hypotenuse is called the cosine of the angle. Thus, Fig. 28,

$$\frac{\text{length side } b}{\text{length hypotenuse } c} = \text{cosine of angle } 37^\circ$$

Of course we may also take the ratio of side *a* to side *b*, and give this ratio a name, and this is done in mathematics, the ratio being called tangent of the angle 37°. But for our purposes in this book we shall confine ourselves to the two ratios above defined as sine and cosine. The words are usually shortened to the form, sin and cos.

From what has been stated above, it should be evident to the student that if the angle 37° in a right triangle always fixes the lengths of the sides of the triangle so that the ratio of the side opposite the angle to the hypotenuse is 0.6 and the ratio of the adjacent side to the hypotenuse is 0.8, then for any other angle the corresponding ratios must be different. In other words each angle has its own exact value of sine and cosine. Thus, referring again to Fig. 28, let us find the sine and cosine of 53°.

$$\sin 53^\circ = \frac{\text{side opposite}}{\text{hypotenuse}} = \frac{4}{5} = 0.8$$

and

$$\cos 53^\circ = \frac{\text{side adjacent}}{\text{hypotenuse}} = \frac{3}{5} = 0.6$$

Note here a very important fact, namely, that in the triangle discussed, the sine of the angle 53° is the same as the cosine of the angle 37°.

$$\sin 53^\circ = 0.8 = \cos 37^\circ$$

and similarly,

$$\sin 37^\circ = 0.6 = \cos 53^\circ$$

This fact is also very helpful to us in solving problems. The angles 53° and 37° are complementary, that is, together they make 90°. Of course in all right triangles, the two acute angles are always complementary and therefore we may generalize as follows: The sine of one of the acute angles in a right triangle is equal to the cosine of the other acute angle.

6. SINE AND COSINE TABLES:

Keeping the above facts in mind, let us now turn our attention to the use of sine and cosine tables. Mathematicians have prepared tables of ratios for all angles from 0° to 90°. Thus, for example, Table I shows the value of the sine for each angle from 30° to 60°. Similarly, Table II shows the value of the cosine for each angle between 30° and 60°. These tables are not complete, but are given here only to illustrate certain points.

TABLE I		TABLE II	
Angle	Sin	Angle	Cos
30°	.5000	60°	.5000
31°	.5150	59°	.5150
32°	.5299	58°	.5299
33°	.5446	57°	.5446
34°	.5592	56°	.5592
35°	.5736	55°	.5736
36°	.5878	54°	.5878
37°	.6018	53°	.6018
38°	.6157	52°	.6157
39°	.6293	51°	.6293
40°	.6428	50°	.6428
41°	.6561	49°	.6561
42°	.6691	48°	.6691
43°	.6820	47°	.6820
44°	.6947	46°	.6947
45°	.7071	45°	.7071
46°	.7193	44°	.7193
47°	.7314	43°	.7314
48°	.7431	42°	.7431
49°	.7547	41°	.7547
50°	.7660	40°	.7660
51°	.7771	39°	.7771
52°	.7880	38°	.7880
53°	.7986	37°	.7986
54°	.8090	36°	.8090
55°	.8192	35°	.8192
56°	.8290	34°	.8290
57°	.8387	33°	.8387
58°	.8480	32°	.8480
59°	.8572	31°	.8572
60°	.8660	30°	.8660

Thus, in Table I, the angle 30° has a sine of .5000. Note that the table carries the ratios out to four decimal places. Note also how the sine increases as the angle gets larger, whereas the cosine decreases as the angle gets larger. Note again the fact that

$$\sin 37^\circ = \cos 53^\circ$$
$$\sin 38^\circ = \cos 52^\circ$$
$$\sin 39^\circ = \cos 51^\circ$$

and in general that the sine of any angle = cosine (90° − that angle). Because of the above fact, tables are usually not printed separately, since one table can be made to serve for both the sine and the cosine. See Appendix Table I.

7. USE OF SINE AND COSINE:

One of the most important uses of these ratios occurs in the equation for calculating the power in an alternating current circuit.

$$P = EI \times \cos \text{ (some angle)}$$

Power is equal to voltage × current × the cosine of an angle. Let us assume this angle to be 30° in a given case. If $E = 220$ volts, $I = 40$ amperes, the power in this case is

$$P = 220 \times 40 \times \cos 30^\circ.$$

From the cosine table we find that $\cos 30^\circ = .8660$. Hence,

$$\begin{aligned} P &= 220 \times 40 \times .8660 \\ &= 7620.8 \text{ watts.} \end{aligned}$$

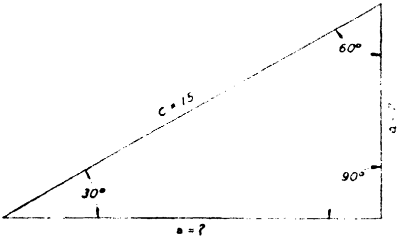


FIG. 29

A common use of the sine and cosine values is in connection with unknown sides or angles of right triangles. In Fig. 29, we have a right triangle whose hypotenuse is 15 units in length. One of the acute angles is 30°, the other, 60°. The problem is to find the length of a and of b. Side a is opposite 30°. So the ratio

$$\frac{\text{Side } a}{\text{hypotenuse}} = \sin 30^\circ$$

or

$$\frac{a}{15} = \sin 30^\circ$$

From the sine table we get sine 30° = .5000. Therefore,

$$\frac{a}{15} = .5$$

and solving for *a*, we have,

$$a = .5 \times 15 = 7.5$$

Side *a* is 7.5 units long or it is half as long as the hypotenuse, which we could have guessed since sin 30° = .5. Also, side *b* is adjacent to angle 30°. Hence

$$\frac{\text{side } b}{\text{hypotenuse}} = \cos 30^\circ$$

or

$$\frac{b}{15} = \cos 30^\circ$$

From the table cos 30° = .8660

Therefore

$$\frac{b}{15} = .8660$$

and

$$b = .8660 \times 15 = 12.99$$

or side *b* is 12.99 units long.

8. GRAPHICAL SOLUTIONS, VECTORS:

In general, alternating current circuits present problems that can very easily and with sufficient accuracy be solved graphically rather than by use of algebra and trigonometry or even higher mathematics. The student is familiar with arithmetic addition and subtraction. Numbers may upon occasion also be added or subtracted geometrically. This kind of addition or subtraction is done graphically, by use of a straight-edge, protractor, compass, and scale.

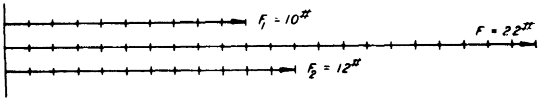


FIG. 30

Consider two boys pulling together on the same rope, one with a force of 10 lbs., the other with a force of 12 lbs. The two together pull with a total force of 22 lbs. This may be represented graphically by use of lines drawn to scale and arrowheads to show which way the lines (forces) are pointed. Thus, in Fig. 30, F_1 is shown by a line 10 units long pointed to the right. F_2 is shown by a line 12 units long pointed to the right. The two together, $F_1 + F_2$, are represented by the line $F = 22$ units in length. F is called the resultant of F_1 and F_2. It is the single force which is equal in effect to F_1 and F_2 together. These lines used to represent the forces are called vectors. We shall use vectors many times to represent voltages, currents, etc., in our electrical problems.

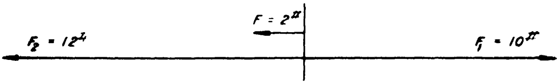


FIG. 31

Note three things about these vectors. First, they have a definite length, scaled off in units to show the size of the force, or voltage, or current, etc. Second, they are drawn in a definite direction—in the above case, horizontally. The two forces are acting along the same straight line and so both are horizontal as also is the resultant F. Third, an arrowhead is used to determine the sense of the force, as toward the left or toward the right along the chosen direction. F_1 and F_2 have arrowheads pointed the same way (toward the right). If the two boys had been playing at tug-of-war, one arrowhead would point toward the right, the other, toward the left, as in Fig. 31. In this case $F_1 - F_2 = -2$ lbs. The arrowheads have the same meaning here as the algebraic signs + and —.

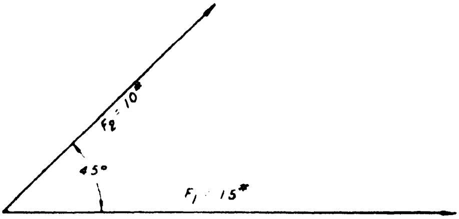


FIG. 32

Now take the two forces $F_1 = 10$ lbs. and $F_2 = 15$ lbs., and let us assume them applied to the same object but making an angle of 45° with each other. See Fig. 32. We can picture these two forces by vectors F_1 and F_2 45° apart, as shown. But how are we to add them? This is done by making a parallelogram out of the figure in the illustration. Thus in Fig. 33, from the tip of F_2 we draw a line parallel to F_1, and from the tip of F_1 we draw a line parallel to F_2. These lines meet at the point B. Now draw the line AB (diagonal of the parallelogram). AB is the geometric or vector sum of F_1 and F_2. In other words, it is F, the resultant of the two forces F_1 and F_2 when added at 45°. Added at any other angle the sum would of course be different. To find the value of F we measure its length on the same scale as was used to lay off F_1 and F_2, and we learn that F equals 23.2 lbs. Observe that the resultant F is the diagonal *between* the two forces F_1 and F_2. The other

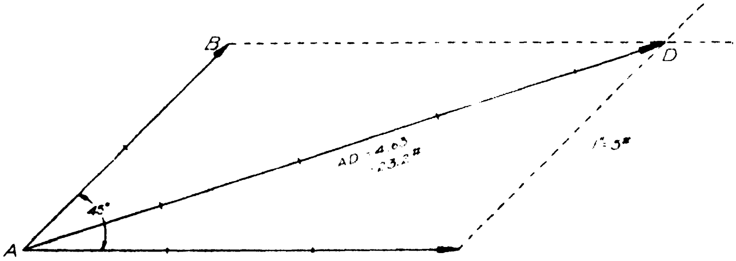


Fig. 33

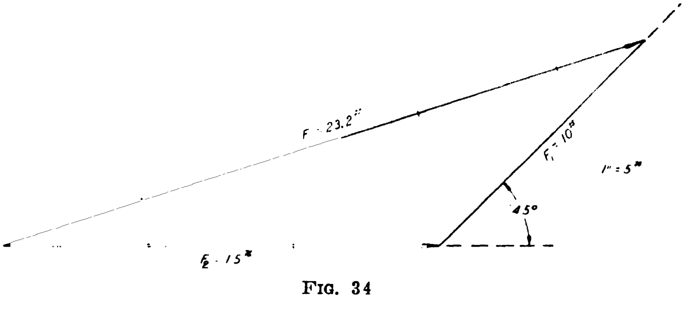


Fig. 34

diagonal CD can be shown to be the difference between F_1 and F_2.

In drawing the diagram in Fig. 33, F_1 and F_2 were both begun at the point A, and the resultant began at point A. It would be just as convenient to draw this diagram as a triangle instead of a parallelogram. See Fig. 34. Draw $F_2 = 10$ lbs. as before. From the head of F_2 draw F_1 at the angle 45° as shown. The resultant F is the third side of the triangle, from the tail end of F_1 to the head end of F_2. The tail of F_2 begins at the head of F_1 in this picture. For convenience we shall call this *head-to-tail* method of adding vectors the triangle method to distinguish it from the parallelogram method.

PROBLEMS—CHAPTER I

1. Draw a line AB, 2 in. long. Erect a line $\perp$ to AB at the middle of AB.
2. Erect another $\perp$ to the line AB at a point ½ in. from the end B.
3. Draw angles of 30°, 45°, 50°, 75°, by use of straight edge and protractor.
4. Bisect an angle of 45° to get angles of 22½°.
5. Draw an angle of 120° and bisect it.
6. The voltage in a certain electrical circuit remains constant at 120. The current then depends upon how much resistance is connected in the circuit. Assume that we have successively 5, 10, 12, 15, 18, 20, 24 ohms resistance in this circuit. Find the corresponding currents and plot I as ordinate (Y-axis) and R as abscissae (X-axis). What kind of graph do you get?
7. Power in a circuit depends upon the square of the current. It is calculated by

$$P = I^2R$$

Assuming $R = 12$ ohms constantly the current is successively 0, 1, 2, 4, 5, 7, 9, 10, and 12 amperes, find the corresponding power and plot P against I. P is the dependent variable in this case.

8. The resistance of metals changes as the temperature changes. The resistance of a certain tungsten lamp when cold (no current through it) was 148 ohms. As current was allowed to flow through the lamp, the temperature increased, and the resistance increased also, as set down in the following table:

Current (amperes)	Resistance (ohms)	Current (amperes)	Resistance (ohms)
0.00	148	0.25	173
0.05	150	0.30	182
0.10	154	0.35	193
0.15	158	0.40	206
0.20	165	0.45	220

Plot the values R and I, I being the independent variable.

9. Iron pipe (conduit) is rated in size according to the approximate measure of the inside diameter. What is the approximate area of the hole in a 2-in. pipe?

10. What is the approximate circumference of the inside wall of 2-in. conduit?

11. Assuming the wall thickness of 2-in. conduit to be 0.20 in., what is the cross-sectional area of the pipe wall?

12. The area of wire is measured by circular mils and is found by squaring the diameter of the wire expressed in mils (thousandths of an inch).

$$\text{C.M. area} = (\text{diameter in mils})^2.$$

What is the C.M. area of a wire whose diameter is 0.325 in.?

13. What is the square-inch area of the wire in problem 12?

14. What is the diameter of a cable whose C.M. area is 1,000,000? (Because the cable is stranded your answer may be only approximate.)

15. What is the approximate square-inch area of the cable in problem 14?

16. What is the approximate circumference of the cable in problem 14? Assume the insulation thickness to be 0.25 in.

17. The following table gives the current carrying capacity, also the C.M. area of several sizes of rubber-covered copper wire.

Wire size	C. M. Area	Allowance current carrying capacity
No. 6	26,250	50
No. 8	16,510	35
No. 10	10,380	25
No. 12	6,530	20
No. 14	4,107	15
No. 16	2,583	6

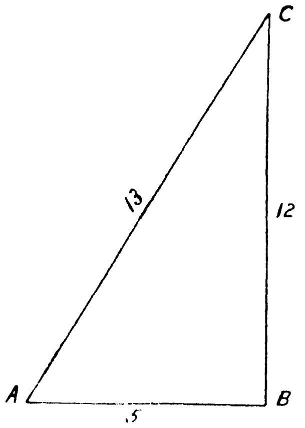
Find the ratio of the C.M. area of No. 6 to the C.M. area of No. 8. Also the ratio of the C.M. area of No. 8 to the C.M. area of No. 10. Figure both to two decimal places. Are these two ratios equal?

18. Write them as a proportion. Then cross-multiply and check the two products for equality.

19. What is the ratio of the allowable current capacity of No. 12 wire to the current capacity of No. 14? Of No. 10 to No. 14?

20. Are the ratios of the current capacities of the wires in problem 19 the same as the respective ratios of the C.M. areas?

21. If 1,000 feet of No. 10 copper wire have a resistance of 1 ohm, what is the resistance of 325 feet of No. 10?



22. If 1,000 feet of No. 16 wire have a resistance of 4 ohms, what is the resistance of 325 feet of No. 16?

23. What is the ratio of the C.M. area of No. 10 copper wire to the C.M. area of No. 16? (See table in problem 17.)

24. What is the ratio of the resistance of 325 feet of No. 10 copper wire to the resistance of 325 feet of No. 16?

25. Are the two ratios of problems 23 and 24 equal? If so, write them in the form of a proportion and check by cross-multiplication.

26. Draw a circle 2 in. in diameter. Divide its circumference into six equal parts. Inscribe a regular hexagon in the circle. Now draw an equilateral triangle inscribed in the circle using the points on the circumference for the vertices of the triangle.

27. A right triangle has a hypotenuse 12 in. long, and one side 4 in. long. What is the length of the other side?

28. The two legs of a right triangle are of equal length, 15 in. How long is the hypotenuse?
29. One side of a right triangle is 5 in. long, the other is 12 in. long. How long is the hypotenuse?
30. Construct the triangle in problem 17. By use of a protractor determine the angles.
31. Given the right triangle shown on preceding page:
    What is the sine of the angle *A*? What is the cosine of the angle *A*?
32. Measure angle *A* and angle *C* by protractor.
33. Look up in the sine and cosine table the value of the sine and cosine of angle *A*. Check these against your answers to problem 31.
34. From the data in problem 31, calculate the sine and the cosine of the angle *C*. Look up the values of the sine and cosine for this angle in the tables and check against your answer.
35. What angles correspond to the following values of sines: 0.1736, 0.3090, 0.5000, 0.7071, 0.8660, 0.9659, 1.0000.
36. What angles correspond to the following values of cosines: 1.0000, 0.9986, 0.9563, 0.8660, 0.7071, 0.5000, 0.3907, 0.2588, 0.0698.

CHAPTER II

VOLTAGE, CURRENT, IMPEDANCE

9. ALTERNATING VOLTAGE:

The commercial method of developing an alternating electromotive force or voltage is by electromagnetic induction. This signifies simply that by means of an electric current, an electromagnet is produced, and by means of the lines of force from this magnet a voltage can be obtained. Fig. 35 shows how a voltage is developed in this way. A coil of wire is connected to a galvanometer and a permanent magnet is thrust through the coil. The galvanometer needle deflects momentarily, showing that a current passed through it. When the magnet is withdrawn, the needle once more deflects, but in the opposite direction. Since current flows, an e.m.f. must have been generated within the coil to have caused the current flow. The latter is small because the e.m.f. causing it is small. The more lines of force, the greater the deflection of the needle, and therefore the greater the e.m.f. produced. Also, the faster the magnet is thrust through the coil, the greater the deflection and therefore the e.m.f.

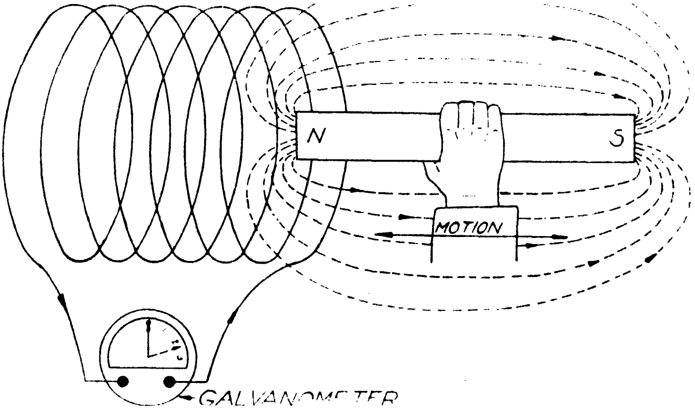
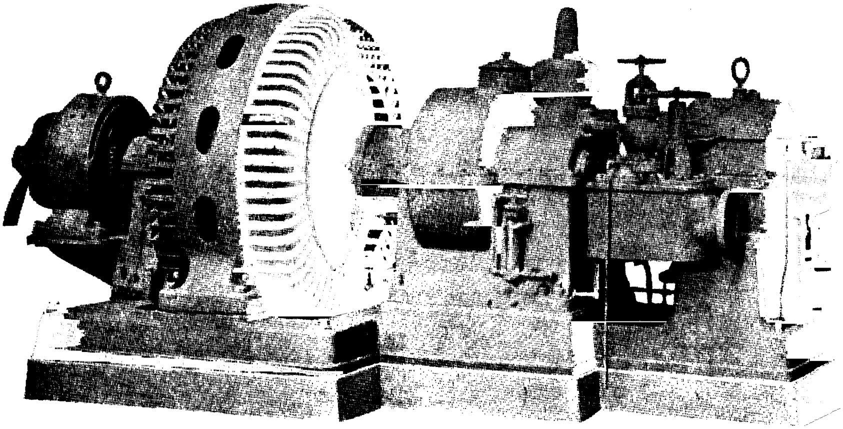


FIG. 35

The large electromotive forces developed by power companies are obtained in this way except that instead of permanent magnets electromagnets are used as the source of lines of force. The machines (Fig. 36) that generate these voltages are called generators. Fig. 37 shows how a generator embraces the three essentials for developing voltage by the induction method. The coil *AB* is the conductor. Lines of force pass from the north pole to the south pole of the electromagnet.



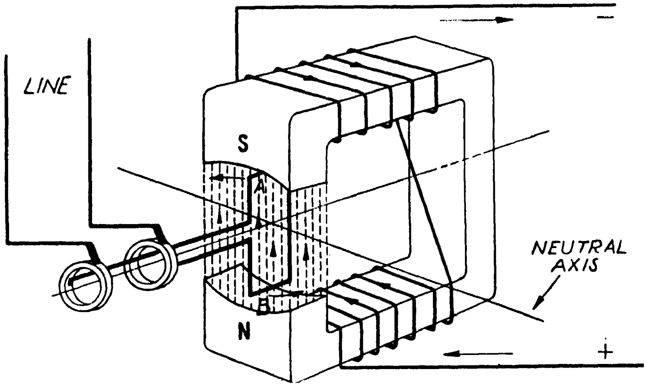


FIG. 37

The coil *AB* is in this magnetic field. Rotation of the coil represents the motion necessary so that the conductors (sides of coil) cut through the lines of force.

We know of currents of electricity that behave like the wave illustrated in Fig. 38. Such currents are called oscillating. They move back and forth in a conductor and as time goes on get smaller in size. The ordinary condenser such as is used in a radio set tends to give rise to such an oscillating current under certain conditions.

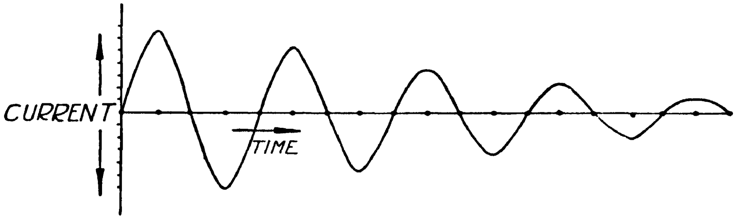


FIG. 38

An alternating current is similar in nature to an oscillating current, but with the difference that the successive oscillations do not get smaller, but remain the same in size. Fig. 39 attempts to picture an alternating current. It differs from Fig. 38 in that all of the waves are of the same size. Let us briefly consider how such a voltage and current are possible.

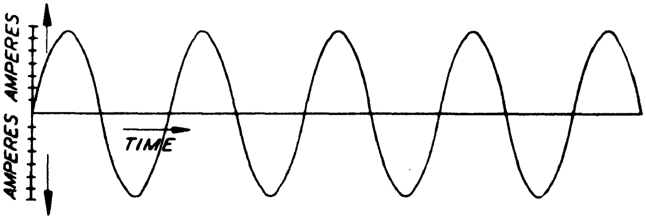


FIG. 39

In Fig. 40 a loop *AB* rotating between two poles of unlike polarity develops a voltage. It has the advantage that two sides of the loop cut the lines of force and so aid each other in generating voltage. The number of volts generated in any case depends upon how rapidly the lines of force are being cut by the wire. When the loop *AB* rotates between the north and south poles in Fig. 40, the two sides of the loop which "cut" the lines of force do not at all instants move through the lines

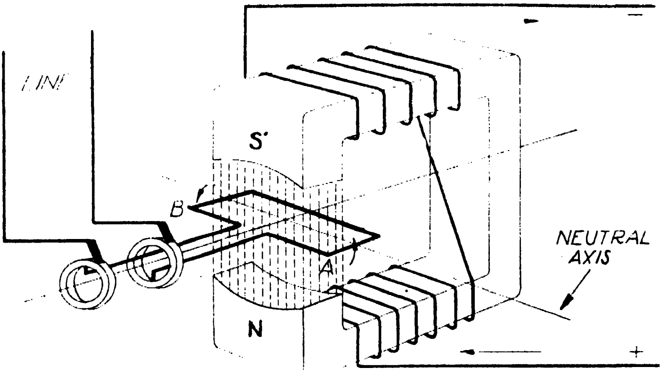


Fig. 40

at right angles. Therefore, they cut the lines at a different rate at each instant. That is, at the instant pictured in Fig. 40 the two effective sides of the loop are moving parallel to the

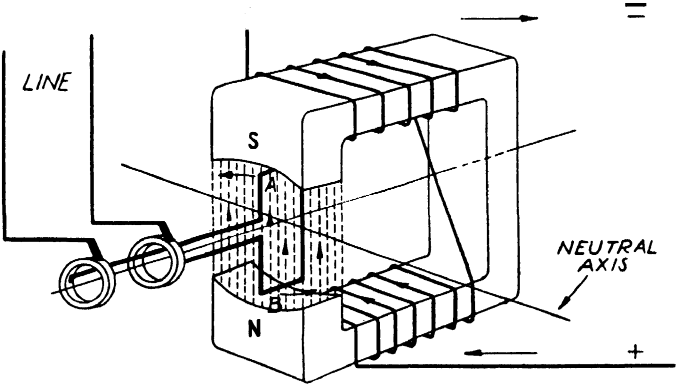


Fig. 41

lines, hence no voltage is generated; while in Fig. 41, these same sides are passing by the middle of the poles. They are moving at right angles to the lines of force and are cutting lines at the highest rate, which means they are developing a maximum voltage in this position. Between these positions of the loop *AB*, the voltage generated is increased from zero (Fig. 40) to the highest value (Fig. 41). Now examine Fig. 42. The loop has advanced through 180° from its original position in Fig. 40. At the instant pictured in Fig. 42, the two effective sides are again moving parallel to the lines of force, and hence no lines are being cut; no voltage is being induced. Between the positions in Fig. 41 and Fig. 42 the voltage developed is decreasing from the highest value to zero. This increasing and decreasing voltage induced by the rotating loop is pictured by the illustration in Fig. 43.

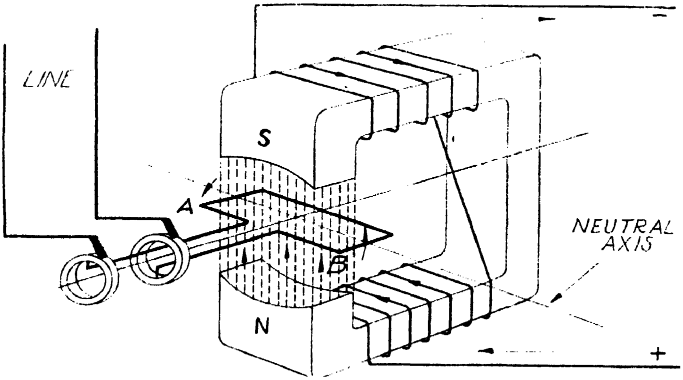


FIG. 42

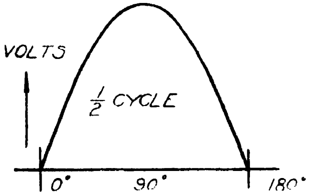


FIG. 43

In Fig. 44 the loop *AB* has now passed through 270° and is once more cutting lines of force at a maximum rate; but now the two active sides of the loop are moving oppositely as compared to the motion in Fig. 41. Fig. 45 pictures the increasing and decreasing voltage induced by the loop *AB* as it completes its revolution from the 180° position back to the starting-point. Note that for this half-revolution the loop is below the line which signifies that if the loop in Fig. 43 is considered positive, the loop in Fig. 45 is negative. This means that the voltage developed during the first half-revolution is opposite that developed during the second half-revolution. Therefore the arrows which are intended to indicate the voltage polarity of the loop ends are reversed, *A* being positive during the first half-revolution and *B*, negative. During the second half-revolution, *B* is positive while *A* is negative.

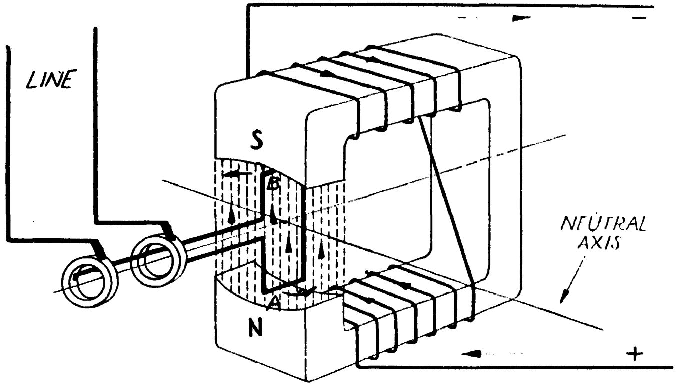


FIG. 44

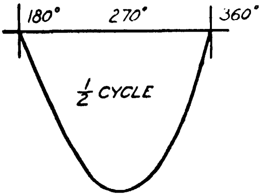


FIG. 45

If we put together the two voltage pictures of Figs. 43 and 45 as is done in Fig. 46, we have a picture that represents the voltage induced by the loop *AB* during one complete revolution. This wave or, as it is commonly called, voltage cycle, is repeated with each revolution of the coil. The result is the series of waves shown in Fig. 47, and as was stated previously in connection with this figure, this series of waves or cycles represents an alternating current or voltage.

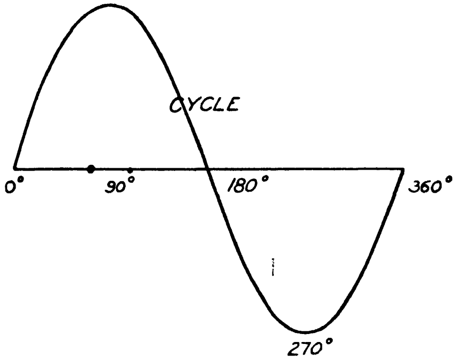


FIG. 46

10. ALTERNATING CURRENT:

It is to be expected that the electric current will be similar in character to the voltage that causes it. If the voltage is alternating, the current resulting will alternately flow back and forth in the conductors and the electrical appliances being supplied. This reversal of current or voltage most commonly occurs 120 times a second; that is, there are 120 *alternations* or *half-cycles* each second. This represents 60 complete cycles.

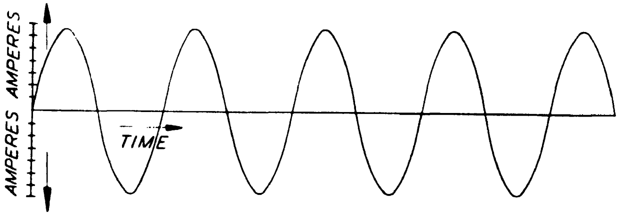


FIG. 47

11. FREQUENCY:

The term "cycle" refers to the complete series of voltage values which the coil *AB* (see previous illustrations) generates in one revolution. This loop rotates between one pair of poles. In one revolution one complete positive loop and one complete negative loop of voltage values is generated. The two together (Fig. 48) complete the "cycle" or series of values. One cycle of voltage is generated each time the loop rotates past one pair of poles. In the previous illustrations this happens once during each revolution of the loop *AB*. The number of cycles developed per second depends, therefore, upon the number of pairs of poles in a machine and also on how fast the generating loops are rotating. To generate a 60-cycle voltage in a two-pole machine, the loops must revolve 3,600 times per minute. A 60-cycle voltage means a *60-cycle-per-second* voltage. To generate 1 cycle per second requires that the loop *AB* rotate past one pair of poles once in one second. To develop 60 cycles per second the loop must rotate past one pair of poles 60 times in one second. This is the same as 3,600 times per minute. The *number of cycles per second* is called *frequency*. From the above it is seen that the frequency is equal to the number of R.P.M. multiplied by the number of pairs of poles divided by 60. Thus if f = frequency, and P = number of pairs of poles,

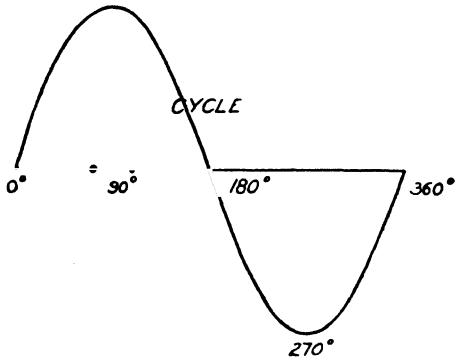


FIG. 48

$$f = \frac{\text{R.P.M.} \times P}{60}$$

Or in the above case

$$f = \frac{3600 \times 1}{60} = 60 \text{ cycles per second.}$$

While the 60-cycle frequency is most commonly employed in this country, other frequencies are also to be found. Thus 25-cycle systems for both light and power are in use, though it is possible at this frequency to observe a slight flickering of the lights. Higher frequencies are employed in connection with experimental work in laboratories, and in recent years 120-cycle and even 180-cycle frequencies are not uncommon for use with motors that drive grinders or wood lathes, higher speeds being the object. Frequencies of several hundred thousand to a million or more per second are used in broadcasting stations.

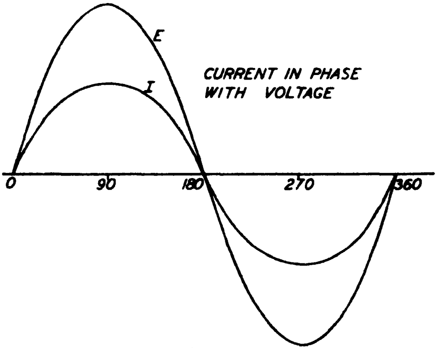


FIG. 49

Obviously the frequency of the voltage is also that of the current. Fig. 49 shows voltage and current cycles together. Observe that here the current increases and decreases in step with the voltage. The current is not always in step with the voltage as we shall learn later.

12. ALTERNATING CURRENT vs. DIRECT CURRENT:

Approximately nine-tenths of the electrical energy used in this country is developed as alternating current. It is more economical to generate and transmit alternating current.

Moreover, alternating current power plants can be built with larger capacities per unit than direct current power plants. Alternating voltages are easily raised or lowered. In many instances also, alternating current motors are preferable to direct current motors. Hence both customer and central station find alternating current to their advantage. Sometimes it is preferable to generate power as alternating current and then to convert it to direct current.

The tendency today is toward larger generating units and higher voltages.

The Detroit Edison Company's Trenton Channel plant has six 60,000 Kva. turbo-alternators. There are turbo-alternators of 75,000 and 90,000 Kva. capacity in operation. The Ford Motor Company has recently installed a 110,000 unit. And the General Electric Company has designed and built for the State Line Station at Chicago one unit of 208,000 kilowatts. This latter generator develops 18,000 volts, weighs 41,000,000 lbs., and receives steam at a pressure of 600 lbs. per square inch. Two tons of coal and 400,000 gal. of condensing water are needed per minute to keep it going.

Probably the most common of the higher voltages at which electrical power is being generated today is about 13,200 at the alternator. These voltages are then raised to 24,000 volts or more by transformers. Voltages of 120,000 are not uncommon.

13. RESISTANCE:

We know that resistance means hindrance effect of a conductor or of an appliance, which tends to limit the current flow. The size of the electric current depends not only upon the voltage that causes the current flow but also upon the hindrance effect of the appliance through which the current flows. Because of the fact that an alternating current reverses itself ordinarily 120 times per second, the resistance offered by a given piece of apparatus is not quite the same when alternating current passes through it as it is when a direct current flows. This is because of a peculiar effect called "skin effect."

Apparently the alternating current behaves as though the conductor in question were hollow. In the case of a wire, the electrons seemingly do not move through the center or core of the wire, but apparently tend to pass through that portion of the copper which is nearest the outside wall of the wire. This effect becomes increasingly noticeable as the frequency of the current increases. For frequencies of several hundred kilocycles this "skin effect" is so pronounced that the current is harmless to the human body even though the voltage causing the current is very large. For the lower frequencies such as 25 cycles or 60 cycles, the effect varies in importance depending upon the conditions. This "skin effect" does, however, make the *alternating current* resistance of a conductor greater than the *direct current* resistance of the same conductor, since the effect is the same as though the cross-sectional area of the wire were less. We shall in our discussions in this text consider resistance to mean actual A.C. resistance or *effective resistance*, i.e., the actual ohms of hindrance that a conductor or appliance offers to the flow of current. There are other factors such as temperature change and eddy currents which affect the A.C. resistance and tend to make it larger than on a D.C. circuit. But we shall not concern ourselves with these. In a very general way it may be said that the resistance of an appliance in an A.C.

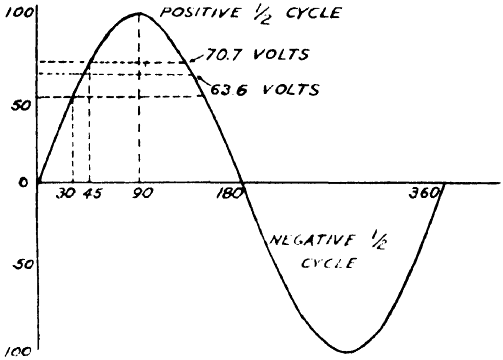


FIG. 50

circuit may be from 5% to 20% greater than on a D.C. circuit, but we shall always state resistance values as they are assumed to be on A.C. circuits.

14. ALTERNATING VOLTS, AMPERES, OHMS:

Since alternating voltages and currents change value from instant to instant, both being actually zero at two instants during each cycle and also at maximum values twice during each cycle, it is essential that the student understand clearly the meaning of "alternating volt," "alternating ampere," and "alternating ohm," so called. Observe in Fig. 50 that the voltage cycle illustrated shows a maximum value equal to 100 volts. The alternating voltage pictured in this illustration passes through all values between zero and 100 volts and back to zero again, over and over, twice each cycle, once during the positive half-cycle, and again during the negative half-cycle. Thus it reaches the value 50 volts twice during each half-cycle, namely at the instants corresponding to the 30°, the 150°, the 210°, and the 330° positions.

Now it must be obvious to the student that an alternating voltage such as is pictured in Fig. 50 cannot be equivalent in effect to a constant voltage (direct) of 100 volts, since the alternating cycle is at the 100-volt maximum value for only one instant during a half-cycle. Moreover, if the average voltage during one half-cycle be computed, we find it to be slightly less than 64 volts or not quite 64% of the maximum voltage (100). What should a voltmeter read if an alternating voltage such as that shown in Fig. 50 were applied to its terminals? Certainly not 100 volts, because except at the instant of the maximum, the voltage is less than 100. Should the voltmeter read 64 volts or the average during each half-cycle? This would seem more reasonable, and in this case would mean that an alternating voltage having a 100-volt maximum would be equivalent to a steady voltage (direct voltage) of 64 volts. An alternating voltage of 100 volts applied to the elements of a toaster should therefore result in a current whose heating effect is exactly the same as the heating effect of a direct current caused by 64 direct volts applied to the same toaster element. ***Experiments, however, show that this is not the case,*** but that the heating effect of the current, due to the alternating voltage (with a 100-volt maximum) is rather the same as that of a current caused by 71 direct volts, or more exactly 70.7 direct volts. This is because the heating effect of an alternating current depends upon the square of the current, so that if the current is doubled the heating effect is quadrupled. So then, an alternating voltage has the same effect as a direct voltage equal to 70.7% of the alternating maximum value. See Fig. 50.

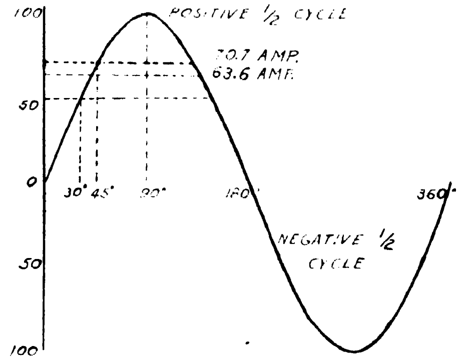


FIG. 51

When we speak of a 110-volt (alternating) lighting system, we mean that the alternating voltage produces the same results as under similar conditions would be produced by 110 direct volts. The maximum value of such an alternating voltage is, of course, greater than 110, since as we have stated previously, 110 volts is only 70.7% of the maximum.

$$110 \div 70.7 = 155.7 \text{ volts.}$$

A voltmeter connected to such a lighting circuit reads 110 volts, not 155 volts. In other words, the voltmeter reads 70.7% of the maximum value of an alternating voltage.

Note the terms that have appeared in this discussion: ***maximum voltage, average voltage, instantaneous voltage.*** To these we add the term *effective voltage*, or *effective current.*

The latter term refers to the 70.7% of the maximum value of an alternating voltage or current. It signifies the equivalent direct current or voltage, and is the value that is recorded by an alternating current ammeter or voltmeter.

From the above considerations it may be stated that the A.C. volt is equivalent in effect to the D.C. volt. Similarly since alternating voltages give rise to alternating currents that vary in value through a cycle (Fig. 51) the A.C. ampere is equivalent in effect to the D.C. ampere. The alternating current cycle also has its maximum value, its instantaneous values, an average value, and an effective value. The latter is 70.7% of a maximum current value and it is this value which the A.C. ammeter records.

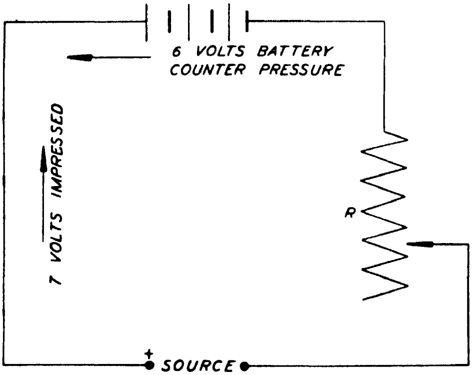


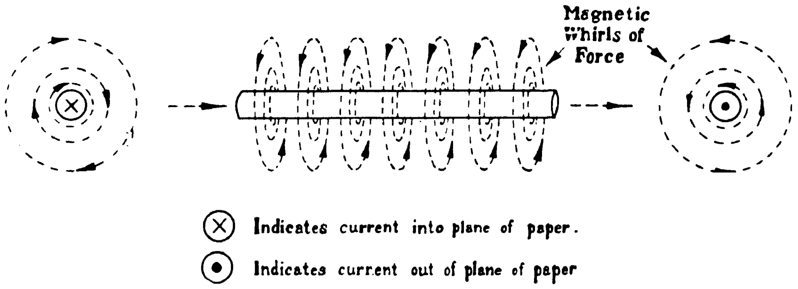
FIG. 52

Finally an ohm represents the unit of resistance that restricts current flow in either a direct or an alternating current circuit. We shall learn presently that in an alternating current circuit, other hindrance to the flow of current is encountered in addition to the ordinary ohmic resistance of the conductors. We call this additional hindrance, *reactance*, and its cause, *inductance*. The succeeding articles are devoted respectively to inductance and reactance.

15. INDUCTANCE, REACTANCE:

Observe Fig. 52. It represents the charging of a storage battery by means of an impressed voltage of 7 volts. The 6 volts of the battery act as a back pressure, counteracting the effect of the 7 volts impressed, so that only 1 volt (7-6) causes current flow into the battery.

Such a counter-voltage or back-voltage effect is always present in a circuit in which the current is changing. Assume a wire, as in Fig. 53, which carries a current and therefore is surrounded by magnetic lines or "whirls" of force. An instant before the current begins to flow, conditions are as in Fig. 54, which shows no current flow, and therefore no magnetic lines of force around the wire. Now, we recall that to induce a voltage electromagnetically we need three elements: a conductor, lines of force, and relative motion between conductor and lines of force. At the instant that current begins to flow through the wire in Fig. 53, the magnetic field begins to build up. We can imagine at that same instant a circular line of force, or "whirl," beginning inside the copper wire as a tiny circle and quickly enlarging to the full diameter shown in Fig. 53. This circular line of force is rapidly followed by others until the magnetic field is at full strength. This pro-



⊗ Indicates current into plane of paper.

⊙ Indicates current out of plane of paper

FIG. 53

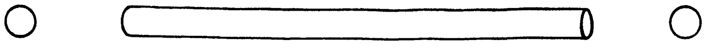


FIG. 54

cedure occurs so rapidly that it seems instantaneous. As a matter of fact, however, it may require several hundredths of a second.

Now, in the procedure just described, we find the three elements needed to generate a voltage. There is a conductor, there are lines of force, and the lines of force to all intents "move" with respect to the conductor or wire *during the time needed to bring the magnetic field to full strength.* Therefore *during this time* there must be a voltage generated by the wire. Experiments show that this is actually so, and moreover that this voltage is always opposite in sense to the voltage which in the first place caused the current to flow in the wire. In other words, we have to do here, as in the case of a charging storage battery, with two voltages: the impressed voltage and the back-voltage or counter-electromotive force. See Figs. 52 and 55. The counter-voltage obviously counteracts in part the effect of the impressed voltage so that the current is smaller than it would otherwise be. But note that the counter-voltage is induced only during the time that the magnetic field is building up. When the circular lines of force have attained full strength or when a steady magnetic condition is reached after some hundredths of a second, the relative motion between wire and lines of force ceases, and hence, also, there is no further induction of a back-voltage to oppose the voltage impressed on the wire. The latter therefore causes current to flow in accordance with Ohm's law, without other opposition than that due to the resistance of the conductor.

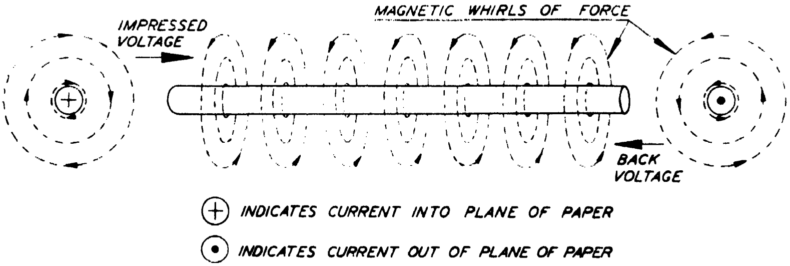

MAGNETIC WHIRLS OF FORCE
IMPRESSED VOLTAGE
BACK VOLTAGE
⊕ INDICATES CURRENT INTO PLANE OF PAPER
⊙ INDICATES CURRENT OUT OF PLANE OF PAPER

FIG. 55

We may summarize the above discussion by stating that *from the moment a direct current first begins to flow* until the magnetic field due to such a current has reached its full strength, a back-voltage is set up in the conductor which opposes the impressed voltage, thus preventing the current from instantaneously reaching its full value according to Ohm's law.

The student should clearly understand that this back-voltage exists only for a very brief time, perhaps one-fifth of a second or less. This back-voltage is often referred to as a self-induced voltage, or voltage due to self-induction, while the peculiar property of a conductor that is subject to such a phenomenon is called *inductance.*

Another important factor about inductance that the student must not overlook is that so long as a current is constant in value no back-voltage is induced. We do not observe this phenomenon, therefore, in direct current circuits except for a few brief instants after the closing of a switch, or while adjustments are being made in the circuit that cause current to fluctuate, or again during the last few instants of flow when the circuit switch is opened.

In the latter case, the circular lines of force built up around the wire while it carries current collapse and disappear, and during this interval a voltage is once more induced. This voltage is the cause of the arc that occurs between the blades and clips of a switch at the time the switch is being opened. Now since inductance and the resulting counter-electromotive force manifest themselves in direct current circuits only during the brief instants that the current is changing in size, they are of little importance in such circuits. On the other hand, alternating currents are at all times changing in size between zero and a maximum value. The magnetic field due to an alternating current is therefore constantly building up and collapsing. These *growing* and *collapsing* circular lines of force are therefore all the time sweeping across the conductor that carries an alternating current, and hence a back-voltage or counter-electromotive force is produced in the conductor all of the time. This self-induced back-voltage is just as effective in limiting the size of the current in the wire as is the back-pressure of a storage battery while the latter is being charged. Refer again to Fig. 52. And because a larger or a smaller back-voltage is present *at all times* in alternating current circuits, it becomes quite essential that inductance and back-voltage be taken into account.

A locomotive moving along a level stretch of track needs merely to overcome the friction (resistance) between the moving parts and between wheels and rails in order to haul its load. On a rising incline, however, the tendency of the locomotive to move "down hill" due to gravity, must also be counter-balanced by the force applied to the driver wheels. In the latter case the force applied does two things: one portion of this force counter-balances the force of gravity tending to move the locomotive down the incline, the other portion of the applied force overcomes the friction. This is somewhat analagous to the situation that exists in an electrical circuit

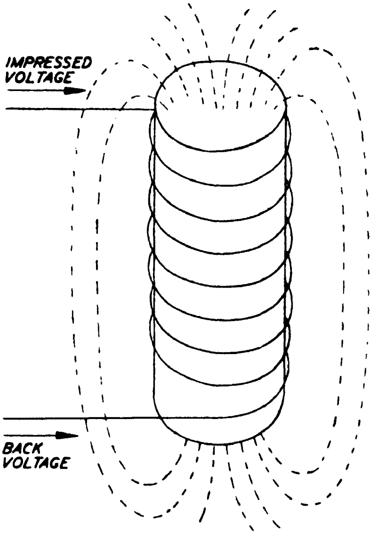


FIG. 56

in which, due to inductance, a back-voltage is induced. The impressed voltage must do two things: one portion must counteract the back-voltage; the other portion of the impressed voltage must overcome the resistance offered by the conductor.

Inductance and the resulting counter-electromotive force are much more noticeable when alternating current flows through a coil of wire than when it flows through a single loop of wire or through a straight conductor. This is because at any instant each loop in a coil carries current in the same direction and hence the magnetic effects of the several loops are *cumulative*, that is, they add one to another, so that the lines of force around any one conductor tend to link themselves with all conductors of the entire coil. (See **Fig. 56.**) Thus the back-electromotive force becomes comparatively large and hence the impressed voltage is able to cause a smaller current flow than would otherwise result. Coils are, therefore, often used to "choke" current surges, or sudden rushes of current, due to short-circuit or other causes. Such a coil is shown in Fig. 57, and is called a ***reactor*** or ***choke coil.***

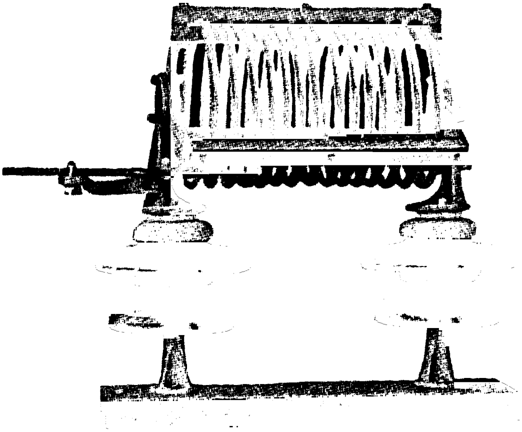


FIG. 57

Inductance is measured in ***henrys*** or millihenrys. The latter unit is more common because the henry is a rather large amount of inductance. The student is perhaps familiar with the unit millihenrys as applied to coils used in radio sets. We

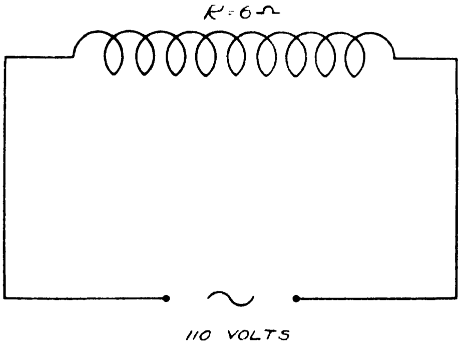


FIG. 58

are not so much concerned in this text with inductance itself as we are with the opposition or hindrance effect to the flow of current that results from inductance.

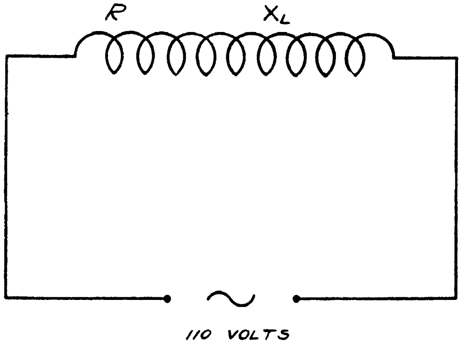


FIG. 59

16. INDUCTIVE REACTANCE X_L:

Quite obviously, if a coil of wire (Fig. 58) having a resistance ***R*** of 6 ohms is connected across a 110-volt alternating source, the current that flows depends not merely upon the impressed voltage and the opposing resistance, but also upon the back-voltage opposition due to the inductance of the coil. In order to indicate that a coil has an inductive effect we shall ordinarily use the symbol X_L, together with R for resistance, in connection with the coil. Thus, Fig. 59 shows the same wire coil as the previous illustration, the letter R indicating that the coil exerts a resistance effect and the symbol X_L indicating that the coil also offers an inductive opposition. To determine how much current flows in the coil in Fig. 59, we must know not only the impressed voltage and the resistance, but also the opposition or hindrance effect of the coil due to its inductance. We call this latter hindrance effect *reactance.* Reactance is similar to resistance in that both hinder the flow of current. Reactance is different from resistance in that the hindrance effect of the former is a back-voltage effect, while the hindrance effect of the latter is due to the nature and dimensions of the material conductor.

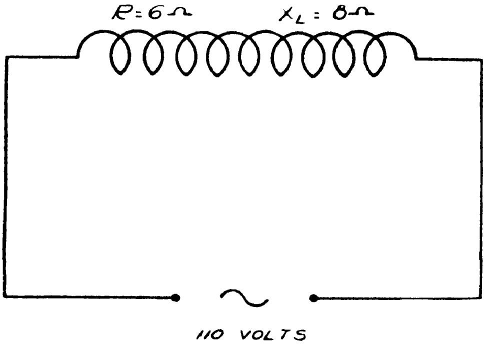


FIG. 60

To compute the reactance of a coil in ohms, we must know the inductance of the coil and the frequency of the circuit in which the coil is being used. The formula for this calculation is

$$X_L = 2\pi f L$$

in which f is the frequency in cycles per second, and L is the inductance in henrys. Thus on a 60-cycle circuit a coil whose inductance L is 0.05 henrys has a reactance effect of 18.85 ohms.

$$\begin{aligned} X_L &= 2\pi f L \\ &= 2 \times 3.1416 \times 60 \times .05 \\ &= 18.85 \text{ ohms} \end{aligned}$$

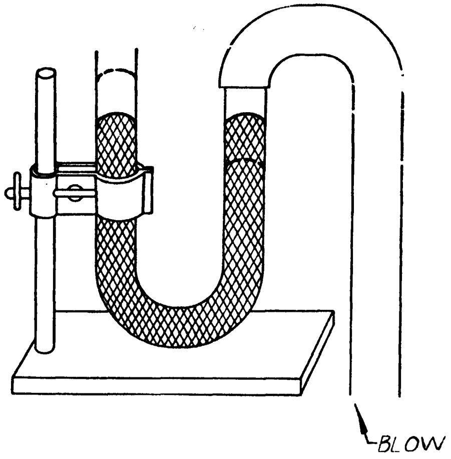


FIG. 61

Fig. 60 once more shows the wire coil of the previous illustrations, and now both hindrance effects are definitely expressed: $R = 6$ ohms, $X = 8$ ohms. It is now possible to cal-

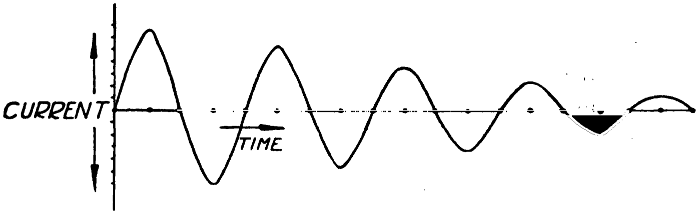


FIG. 62

culate the current that flows through the coil, since we know the impressed voltage and also the resistance and the reactance. The student should not jump to the conclusion that the current is to be found by adding the two effects arithmetically, 6 + 8 = 14 and then dividing 110 by 14. For reasons that will appear presently, it is necessary that these two hindrance effects be added *geometrically*, not arithmetically.

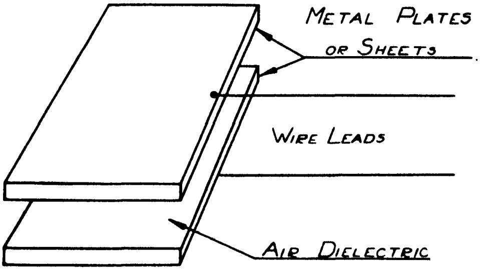


FIG. 63

7. CAPACITY REACTANCE X_C:

Examine Fig. 61. If we blow into the tube as shown in the illustration, the mercury will rise in the left leg of the glass tube and will fall in the right. As soon as the air pressure is removed, the mercury tends to assume its original level in

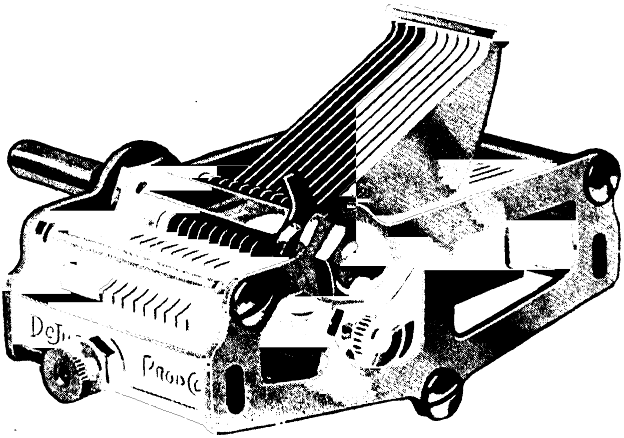


FIG. 64

both legs of the tube. Several seconds elapse before the mercury comes to rest; meantime it oscillates back and forth in the tube, each rise and fall being smaller than the preceding ones, until rest is attained. The successive oscillations of the mercury might be represented as in Fig. 62, and the flow of mercury back and forth might be considered similar to an oscillating electric current. Such electric currents are actually met with in condensers. A condenser consists of two con-

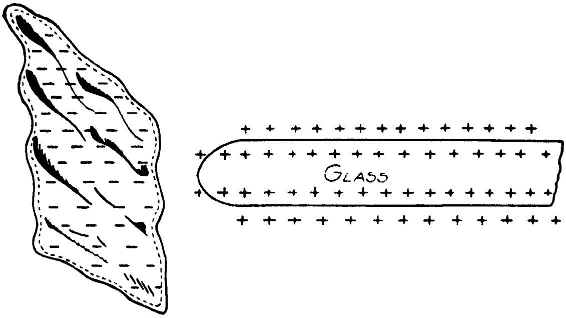


Fig. 65

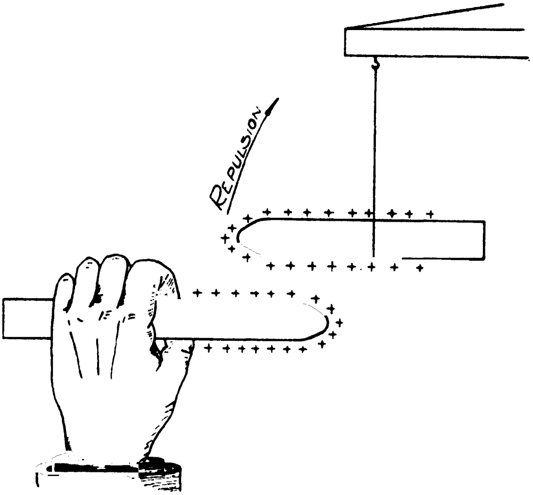


Fig. 66

ductors separated by a non-conductor (also called dielectric). Thus (Fig. 63), two strips of sheet aluminum separated by air constitute a condenser. The student is undoubtedly familiar with the form of condenser used in radio receiving sets. See Fig. 64.

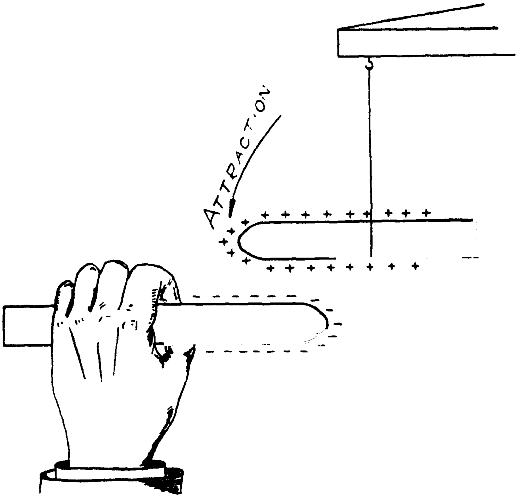


FIG. 67

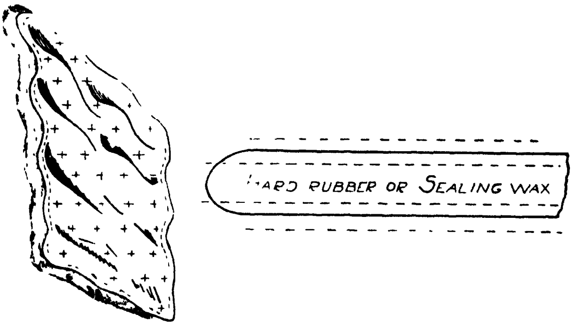

HARD RUBBER OR SEALING WAX

FIG. 68

18. ACTION OF CONDENSER:

Our discussions concern almost exclusively electricity in motion, or current electricity. Electricity, however, is sometimes at rest, and then we call it *static electricity.* A glass rod rubbed with a silk cloth shows ability to pick up bits of paper, or to repel another glass rod similarly "charged." Or again such a glass rod will attract a stick of hard rubber that has been rubbed with a flannel cloth. See Figs. 65-68. A moving belt, as it passes over the pulley also develops static electrical charges by friction. Another common manifestation of static electricity occurs when dry hair is being combed with a rubber comb.

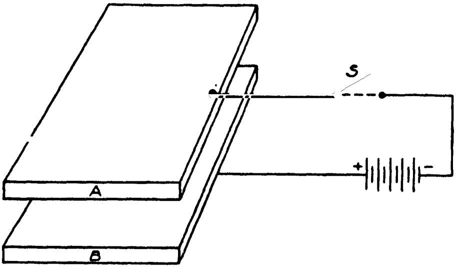


Fig. 69

The two plates of a condenser store charges of electricity in a similar manner. If we join the two plates to a source of voltage, as in Fig. 69, it is clear that since the aluminum plates *A* and *B* are separated by air, there can be no electric current flow in the circuit in the sense that we ordinarily think of when we speak of electric currents. Nevertheless there is a momentary flicker of the galvanometer needle (Fig.

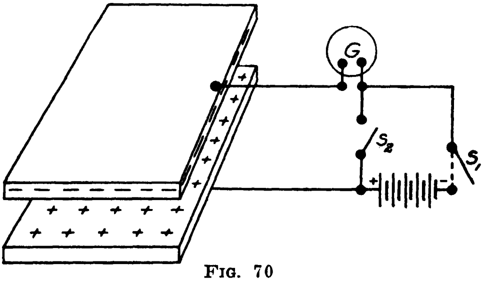


Fig. 70

70) at the instant that the switch S_1 is closed. For an instant at least there is apparently a flow of electricity or what for want of a better term might be called "electric charges," one plate gathering the positive charges and the other the negative. If, now, S_1 be opened, the condenser remains charged, that is, a small quantity of electricity is stored on the plates A and B. This can be shown by closing switch S_2, which once more connects the galvanometer to the plates, but omits the source. Again the galvanometer needle will momentarily deflect, this time in the opposite sense, showing that for an instant an electric current again flowed. And if we studied the discharge of the condenser carefully enough we should

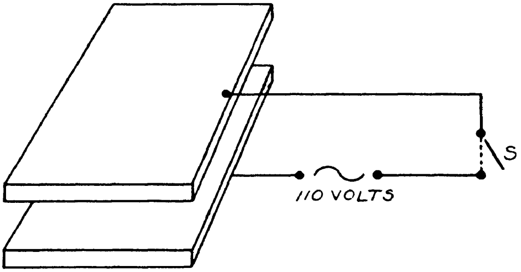


Fig. 71

find that the current flow, while lasting for a very brief time, was an oscillating current such as was pictured in Fig. 63.

Now in Figs. 69-70 we assumed that the condenser was being charged from a source of *direct voltage*, let us say, 110 volts. The condenser plates when charged were therefore at a potential difference of 110 volts. Let us now assume an alternating voltage applied to the condenser plates as in Fig. 71. And let us further assume that the switch S is actually closed at the instant of zero voltage. During the succeeding instants of the voltage cycle up to the time that the voltage reaches its maximum value, a charging current flows into the condenser, not momentarily as before, but continuously because the voltage is constantly rising until the voltage reaches its peak value at the instant of the maximum. At this moment the source is at its peak voltage and the condenser is charged to this peak voltage. Hence current flow is zero at this moment. An instant later the charging voltage begins to drop off. At once the condenser (which has been charged to the peak voltage) is able to discharge because the source has now dropped below the peak. Current flows out of the condenser and continues to flow out until the condenser itself is at zero difference of potential.

It must be emphasized here that the current flow into or out of the condenser is not a current passing through a conductor in the ordinary sense, for we know that the plates *A* and *B* are separated by air which makes the resistance of the circuit practically infinite. It is a charging current that shuttles back and forth between condenser plates and source, and which because it is appreciable enough to be indicated by an A.C. ammeter becomes sufficiently important to warrant our attention. Moreover, just as inductance effects are to be observed in greater or less degree, so too are condenser effects to be found. In a transmission line, for example, we have metal conductors separated by air, which arrangement constitutes a condenser whose effect, especially under certain conditions, cannot be neglected.

Note, too, that when the condenser plates are connected to an alternating voltage source, the current is *limited*, or restricted in size. Hence the condenser, too, exercises a controlling effect or hindrance effect on the amount of current flow. This hindrance effect is measured in ohms and is also called *reactance.* But in order to distinguish it from the hindrance effect due to the inductance of a coil, the latter is called *inductive reactance*, represented by the symbol X_L, while the former is called *capacity reactance*, represented by the symbol X_C. *Capacitance* is another name sometimes used instead of capacity reactance.

Capacity reactance also must be expressed in ohms in order to use it in connection with resistance and inductive reactance. And in order to compute the capacity reactance of a condenser we can use the equation

$$X_C = \frac{1}{2\pi fC}$$

in which f is the frequency in cycles per second and C the capacity of the condenser in farads. The farad is a very large unit, so that often the capacity of condensers is given in microfarads, or millionths of a farad.

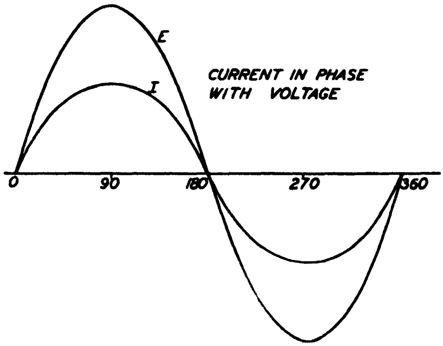


FIG 72

Note how much like the equation for inductive reactance, the above equation is:

$$X_L = 2\pi fL \qquad X_C = \frac{1}{2\pi fC}$$

But in the case of X_C, the term $2\pi fC$ is in the denominator. This suggests that while X_L and X_C, both have a hindrance effect on current flow in a circuit, the two do this quite differently. As a matter of fact X_L and X_C have opposite effects on the current in a circuit, in that X_L always tends to make the current lag behind the voltage, while X_C always causes current to get ahead of, or lead, the voltage. Resistance simply opposes the current flow.

Figs. 72, 73, and 74 show these conditions. Note that the current and voltage rise and fall together in Fig. 72. The zero and the maximum for current and voltage always come at the same instant. This is the case in circuits in which only resistance is present. In Figs. 73 and 74, the zero and maximum values of current and voltage do not come together. The current waves do not rise and fall in step or in time with the voltage wave. In Fig. 73, the current is behind, which is typical of circuits that contain X_L, whereas in Fig. 74 the current is ahead of the voltage, which is a typical condition for circuits containing X_C. Circuits may, of course, include all three forms of hindrance, R, X_L, and X_C and then the current and voltage may or may not be out of step, depending upon the predominance of R or X_L or X_C. We shall learn more about this in the next chapter.

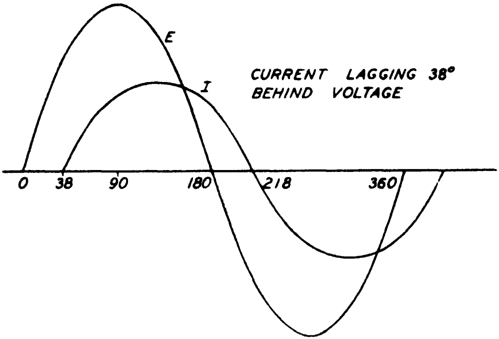


FIG. 73

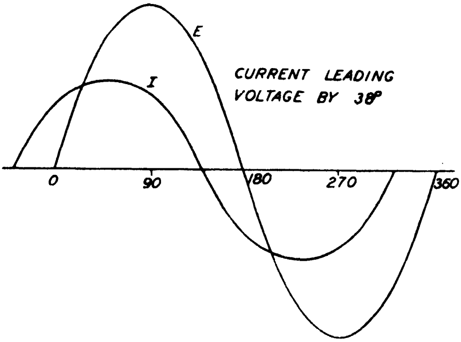


FIG. 74

19. IN PHASE, OUT OF PHASE:

The term *phase* refers to time. Two pendulums, both beating seconds may swing together all the time, or they may swing out of step with each other. Thus one pendulum may be at the extreme left side of its swing while the other is at the extreme right. To say that the two pendulums are *out of phase* is merely another way of saying they are out of step. Similarly, *in phase* means in step. As we have just seen, currents and voltages in alternating circuits are frequently out of phase with each other. So, too, may one current be out of phase with a current in another branch circuit, or two voltages may be out of phase with each other. A convenient method of indicating these conditions is by use of vector diagrams. Thus, Fig. 75 pictures the same condition as is shown in Fig. 73, namely, that the current is out of step with the voltage by 38° and moreover is behind the voltage. Similarly Figs. 76 and 77 picture conditions which were shown in Figs. 72 and 74, namely, current and voltage in phase and current leading the voltage. These diagrams are more easily made than the sine wave pictures.

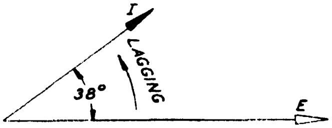


FIG. 75

FIG. 76

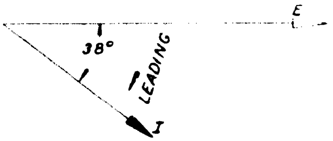


FIG. 77

The maximum out-of-phase condition between current and voltage is 90°. Theoretically, a current may lead or lag by 90°. In practice this condition may be closely realized, though the current is never exactly 90° behind or ahead of the voltage.

20. IMPEDANCE:

We have now discussed three forms of opposition or limitation to the flow of an alternating current: resistance R, inductive reactance X_L, and capacity reactance X_C. Before we can determine how much current will flow in any circuit on which voltage is impressed, we have to know the combined effect of all three forms of opposition. In other words we have to combine R and X_L and X_C to get the total ohms in the circuit. Then, the voltage divided by this total ohms effect is equal to the current. This total hindrance effect in ohms is called *impedance* and is symbolized by the letter Z. Impedance is the combined effect of resistance, inductive reactance, and capacity reactance in any circuit. Let us examine several cases to determine just how R, X_L, and X_C may be combined to obtain Z.

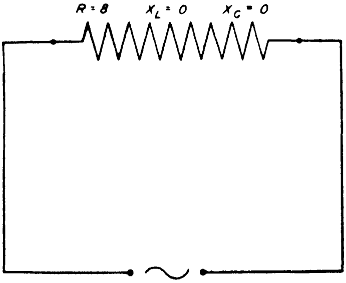


FIG. 78

Assume a circuit such as is shown in Fig. 78. This circuit contains resistance but X_L and X_C are too small to be taken into account and are indicated as zero. Such a condition is realized in the case of a water rheostat, ordinary lamp bulb, or a carbon rheostat. The total hindrance to current in this case is R, since X_L and X_C are zero. Therefore

$$Z = R$$

in this case.

Similarly we might assume a condition in which R and X_C are negligible. Thus a heavy choke coil may have so little resistance that we could consider it zero. X_C would also be negligible. Hence such a coil would oppose current flow only by its X_L ohms. In this case

$$Z = X_L$$

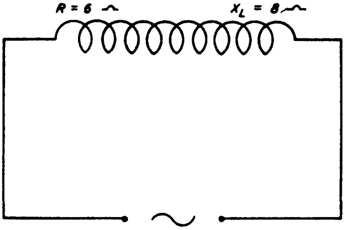


FIG. 79

A condenser used alone in a circuit opposes the flow of current by its capacity reactance. R and X_L are not present. Hence in such a circuit

$$Z = X_C$$

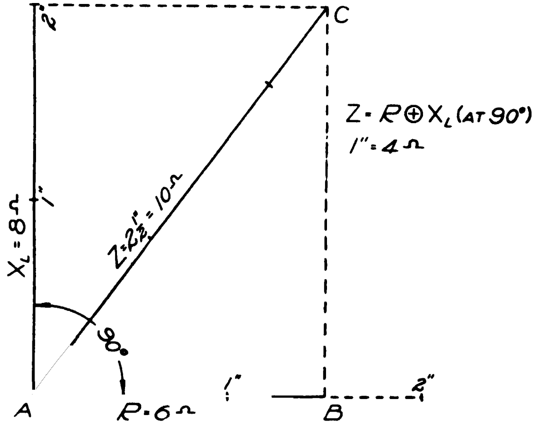


FIG. 80

In most instances circuits involve both resistance and at least one form of reactance. Z is then found by vector addition or graphically. Thus Fig. 79 shows a coil which exerts both a resistance and reactance effect. $R = 6$ ohms, $X_L = 8$ ohms. The total ohmic opposition or Z is

$$Z = 6 \oplus 8$$

Note the symbol $\oplus$. This means added by vectors. But to add 6 and 8 by vectors we have to add at an angle. What angle is this to be? It is always 90°. Reactance tends to throw the current out of step by 90°. Hence X_L is added to R at an angle of 90°. See Fig. 80. Thus Z in this case is 10 ohms. Note the scale chosen is 1 in. = 4 ohms.

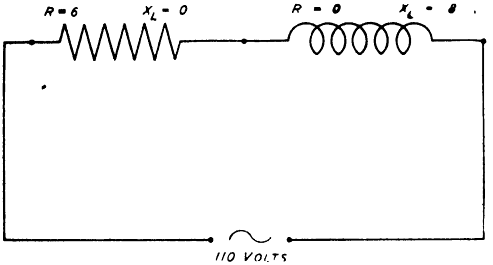


FIG. 81

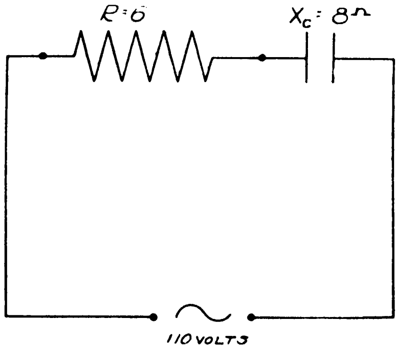


FIG. 82

The case just discussed assumed that the one coil exerts both a resistance and a reactance effect. Suppose that a pure resistance were combined in a series circuit with a pure inductance coil as in Fig. 81. Again Z is found by

$$\begin{aligned} Z &= \mathbf{R} \oplus X_L \\ &= 6 \oplus 8 \\ &= 10 \text{ ohms} \end{aligned}$$

the vector diagram being just as in Fig. 80.

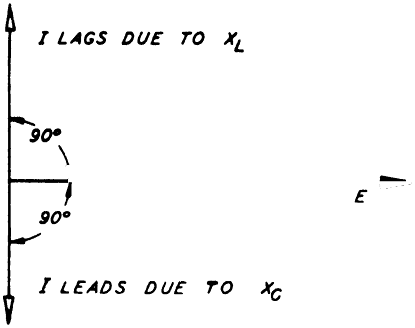


FIG. 83

In place of the coil in Fig. 81 insert a condenser whose capacity reactance is 8 ω as shown in Fig. 82. Now find Z. Again R and X_C are combined by vectors at 90°, but this

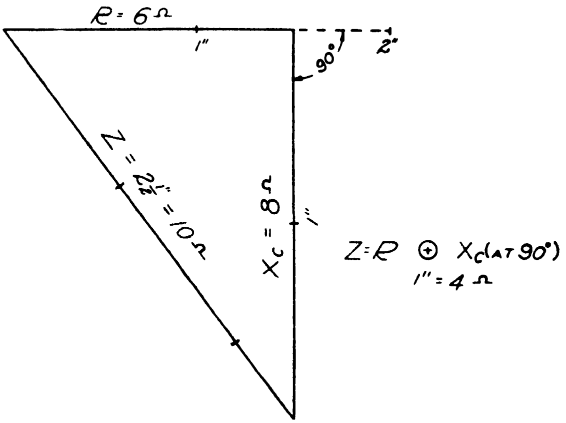


FIG. 84

time with the difference that we must take into account the fact that capacity reactance tends to make the current lead by 90°, whereas inductive reactance tends to make it lag by

90°. See Fig. 83. Observe that the two currents are exactly opposite in sense, or 180° apart. If we called one current plus, the other would be minus, which means one current is in its positive half-cycle while the other is in its negative half-cycle.

When adding X_C to R at 90° we draw X_C opposite in sense to X_L in Fig. 80, or as is shown in Fig. 84.

This does not make Z larger or smaller than in the previous case, but it does give the line Z a new direction, whose meaning will be explained farther on.

Finally, assume a circuit in which R, X_L, and X_C are present, as in Fig. 85. Find Z. Here $R = 6$ ohms, $X_L = 4$ ohms, and $X_C = 8$ ohms. Let us first draw the vector diagram indicating these values. Fig. 86. Note that X_C and X_L are in the same straight line, and that they are opposite each other. One is positive while the other is negative. Hence we can combine these two simply by subtracting the longer vector from the shorter, which is like adding a positive and a negative number.

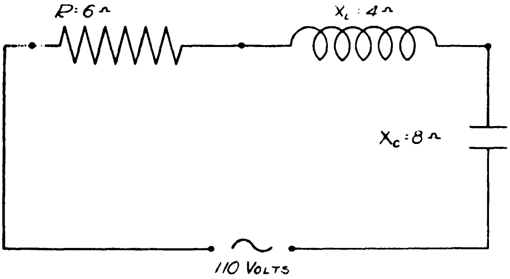


FIG. 85

$$X_L = \oplus 4$$
$$X_C = \ominus 8$$
$$X_L \ominus X_C = -4$$

The minus and plus signs indicate opposite senses. Now we can combine this result with R and we get Z, the combined effect of all three.

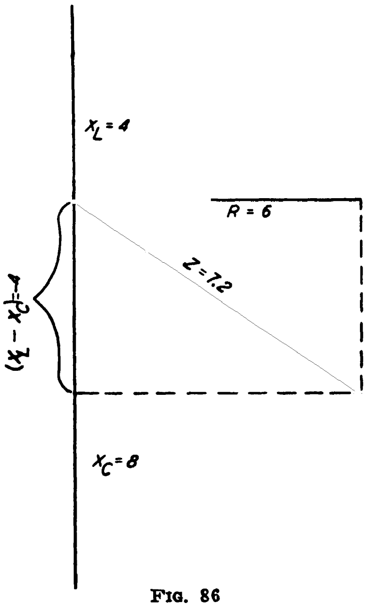


FIG. 86

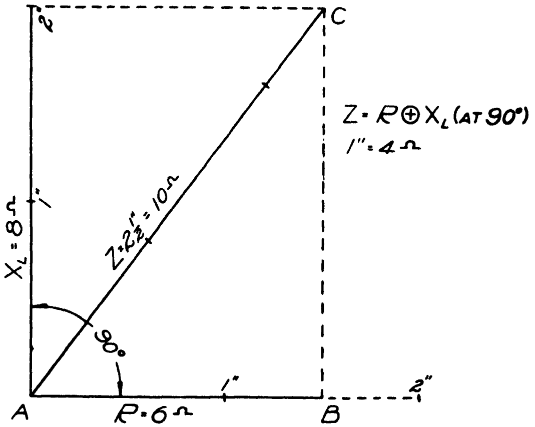


FIG. 87

21. THE IMPEDANCE TRIANGLE:

Instead of solving problems in which *Z* is unknown by adding *R* and *X* by the parallelogram method, a slightly shorter form is commonly used. Examine Fig. 87. The side *BC* is just as long as X_L. Instead of placing X_L at the point A, it could just as well be drawn at B as in Fig. 88. Here only half of Fig. 80 appears, namely the right triangle ABC. AB represents $R = 6$ ohms, BC represents $X_L = 8$ ohms and the side AC closing the triangle represents the vector sum of R and X_L or 10 ohms. This triangle is called the impedance

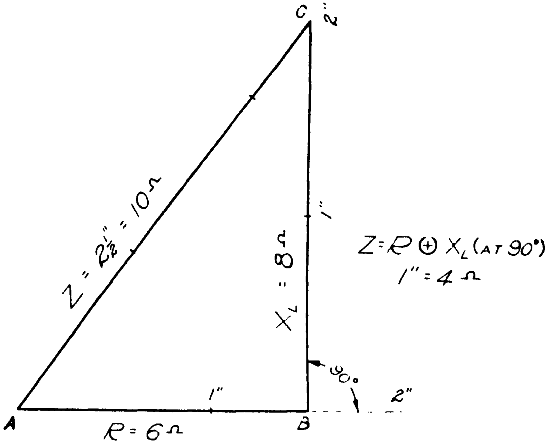


FIG. 88

triangle. Now in triangle ABC note that we can also make use of the right triangle equation

$$c^2 = a^2 + b^2$$

where a and b are sides and c is the hypotenuse. In our case R and X_L are sides, Z is the hypotenuse. We can write

$$\begin{aligned} Z^2 &= R^2 + {X_L}^2 \\ Z &= \sqrt{R^2 + {X_L}^2} \\ Z &= \sqrt{36 + 64} = \sqrt{100} \\ Z &= 10 \text{ ohms} \end{aligned}$$

This gives the same result as the vector method and is true also in the case of X_C even though we use the minus sign to denote opposite sense. Thus Fig. 84 shows R added to X_C.

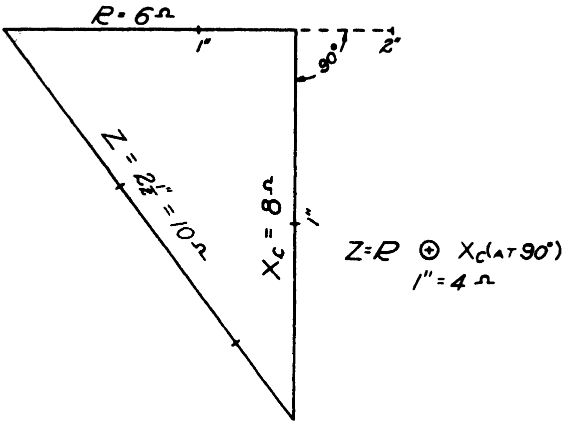


Fig. 89

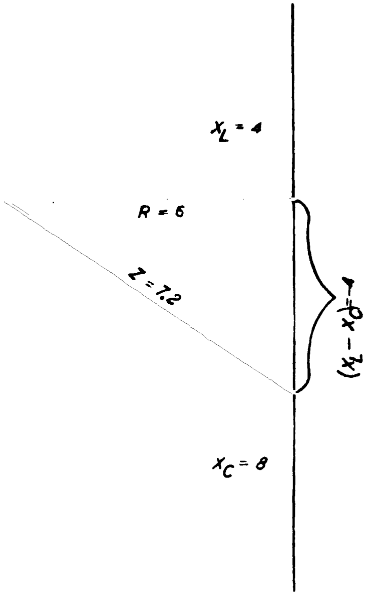


Fig. 90

The impedance triangle would be as in Fig. 89. Using the right triangle formula again we have

$$\begin{aligned} Z^2 &= R^2 + (-X_C)^2 \\ Z^2 &= 6^2 + (-8)^2 \\ Z^2 &= 36 + 64 \\ Z^2 &= 100 \\ Z &= 10 \text{ ohms} \end{aligned}$$

Finally, in the case of circuits involving R, X_L, and X_C, again the impedance triangle can be used as shown in Fig. 90. And so too can we use the right triangle formula. In this case it is

$$\begin{aligned} Z^2 &= R^2 + (X_L - X_C)^2 \\ &= 6^2 + (4 - 8)^2 \\ &= 36 + 16 = 52 \\ Z &= 7.2 \text{ ohms} \end{aligned}$$

PROBLEMS—CHAPTER II

1. Construct a sine wave of voltage. Ask your instructor how to do this accurately if you do not know how. Use as the maximum value 100 volts. Beginning at 5°, measure the value of the instantaneous voltage for every 10° interval (that is, for 5°, 15°, 25°, etc.) up to 175° inclusive. Set these values down in tabular form. Now add these and find the average value of the voltage during the half-cycle by dividing by the number of intervals (18). This should give approximately 63.6 volts. How close is your result?
2. Using the table prepared in problem 1, square all the instantaneous values of the voltage and set down the results in a column. Add these. Divide by 18 to get the average, and then extract the square root of the average. If your work was carefully done your answer should approximate 70.7 volts, or the effective value of the voltage during the half-cycle.
3. A 4-pole generator makes 1,800 revolutions per minute. What frequency does it develop?
4. At what speed in R.P.M. would a 4-pole generator develop 25 cycles per second?
5. If the speed is 900 R.P.M. and the frequency is 60 cycles per second, what is the number of poles in the generator?
6. If the maximum value of an alternating current is 50 amperes, what is the average value of the current?
7. What is the effective value of current in problem 6? What should an ammeter read in such a circuit?

8. If the lights in your home are on a 115-volt circuit, what does a voltmeter read if connected across your lights?
9. What is the peak or maximum value of the voltage on your lighting system?
10. Find the inductance *L* of a transformer coil which has 100 turns of wire, is 25 centimeters long, the area of the steel core is 36 square centimeters, and the permeability of the steel is 1,800.
11. Suppose the steel core is withdrawn from the coil in problem 10, what is the value of *L*?
12. Find the reactance of the coil in problem 10, when it is being used on a 60-cycle circuit.
13. Find the reactance in ohms of the coil in problem 11, if used on a 60-cycle circuit.
14. Find the reactance of the coil in problem 10, when used on a 25-cycle circuit.
15. If the inductance of a coil is .02 henrys, what is the reactance in ohms when used on a 25-cycle circuit?
16. A certain coil has a reactance of 8 ohms on a 60-cycle circuit. What is its inductance in millihenrys?
17. A certain condenser has a capacity of 20 microfarads. What is its reactance (X_c) in ohms when used on a 60-cycle circuit?
18. A group of telephone condensers have together a capacity of 200 microfarads. What reactance do they exert in a 25-cycle circuit?
19. If 10 ohms resistance and 10 ohms inductive reactance are connected in series in a circuit, what is the combined impedance effect?
20. A coil having a reactance of 8 ohms is joined in series to a resistance of 8 ohms and a condenser, whose capacity reactance is 12 ohms. What is the impedance of the circuit?
21. Suppose the capacity reactance in problem 20 is also 8 ohms. What is the impedance for this circuit under these conditions?
22. Draw a vector diagram to show two voltages of 110 volts each, out of phase by 120°. Repeat for an out-of-phase condition of 90°.
23. Draw a vector picture showing a current of 10 amperes out of phase with its voltage of 110 volts by 30°.

CHAPTER III

OHM'S LAW AND POWER

22. OHM'S LAW FOR A.C. CIRCUITS:

In a direct current circuit the current, voltage, and resistance are related to one another in such a manner that if the value of any two of these is known the third can be found. The student is familiar with the forms

$$E = IR$$

$$I = \frac{E}{R}$$

$$R = \frac{E}{I}$$

and also with the fact that these equations may be applied to a direct current circuit as a whole or to any part of such a circuit. May not these same formulas or equations be applied to alternating current circuits?

We have already had occasion to learn that R is not the only factor tending to limit an alternating current and that R must be replaced by Z which is the total opposition to current flow in an A.C. circuit. Hence we shall have to write Ohm's law

$$E = IZ$$

$$I = \frac{E}{Z}$$

$$Z = \frac{E}{I}$$

These equations apply to the circuit as a whole or each may be applied to a portion of a circuit. Thus consider the form $I = \frac{E}{Z}$ as applied to a circuit in which R and X_L are present as in Fig. 91. By vector diagram (Fig. 92) Z is found to be 10 ohms. The current in this circuit is

$$I = \frac{E}{Z}$$

$$= \frac{110}{10} = 11 \text{ amperes}$$

Or knowing the current $I = 11$ amperes and that $R = 6$ and $X_L = 8$ ohms, let us find E. We use the form

$$E = IZ$$

We can first find Z by the impedance triangle, or by the form

$$Z = \sqrt{6^2 + 8^2} = 10.$$

Then,

$$E = IZ$$

$$= 11 \times 10 = 110 \text{ volts}$$

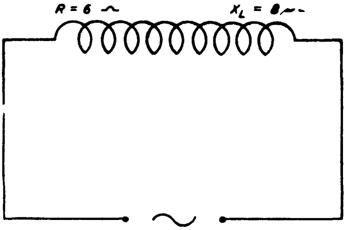


FIG. 91

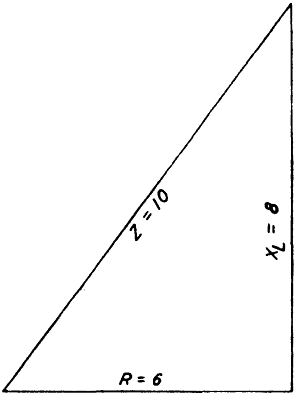


FIG. 92

Or if we wish we can apply the form $E = IZ$ to the resistance and to the reactance of the circuit separately. E is the 110 volts impressed. It must do two things: oppose the back voltage due to the inductance of the coil, and push current through the coil against the opposition of the resistance of the coil. E can be broken up into two parts, one to counteract the back volts, the other to overcome the resistance. Considering the resistance only, we know that to push 11 amperes through 6 ohms resistance requires 66 volts.

$$E_R = IR = 11 \times 6 = 66 \text{ volts}$$

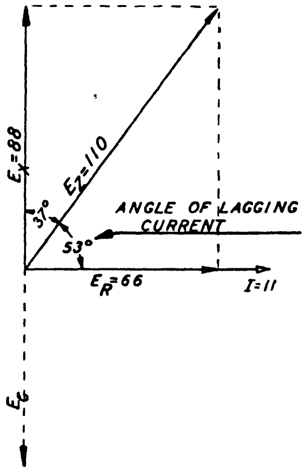


FIG. 93

Considering the reactance X_L only, we know similarly that to counteract the back voltage alone we need

$$E_X = IX_L \text{ volts}$$

or

$$= 11 \times 8 = 88 \text{ volts.}$$

In Fig. 93 we show this graphically. E_X represents the impressed 88 volts which counterbalance the 88 back volts. E_R in phase with the current is the component of the impressed voltage which pushes 11 amperes through the resistance. The two added together

$$E_R \oplus E_X = E_Z$$

or the total impressed volts, which is

$$66 \oplus 88 = 110 \text{ volts.}$$

This vector diagram also shows another important fact, namely, that in the circuit just considered the current 11 amperes lags behind the impressed voltage by 37°. This angle is known as the phase angle, and has an important bearing on the power taken by the circuit.

23. OHM'S LAW SOLUTION OF SERIES AND PARALLEL CIRCUITS:

Let us now solve typical problems by use of Ohm's law.

Problem 1. Resistance and inductive reactance in series. This is the type of problem used in the preceding article. Note that to find the current in the circuit when R, X_L, and E are given, we first find Z by the impedance triangle (Fig. 92) and then use Ohm's law in the form

$$I = \frac{E}{Z}.$$

If I, R, and X_L are given, and E is to be found, use the forms

$$E_R = IR$$
$$E_X = IX_L$$

to find the voltage drop over the resistance, and the voltage drop across the reactance (counteracting back voltage), and add these as vectors at 90°, to find the impressed voltage E. See Fig. 93. If in the above problem the inductance of the coil were given instead of the reactance X_L, then first find X_L from the equation

$$X_L = 2\pi fL$$

Suppose $L = 21.2$ millihenrys, and $f = 60$ cycles per second. In the equation $X = 2\pi fL$, L must be expressed in henrys.

$$21.2 \text{ millihenrys} = .0212 \text{ henrys}$$

So

$$\begin{aligned} X_L &= 2 \times 3.1416 \times 60 \times .0212 \\ &= 6.2832 \times 60 \times .0212 \\ &= 376.992 \times .0212 \\ &= 8.0 \text{ ohms} \end{aligned}$$

In the type of circuit which involves R and X_L in series, the current always lags behind the voltage. The angle is easily found from the vector diagram by protractor. Or it may be calculated. Thus in Fig. 93, the angle between I and E_Z has for its cosine,

$$\frac{E_R}{E_Z} = \frac{66}{100} = .6$$

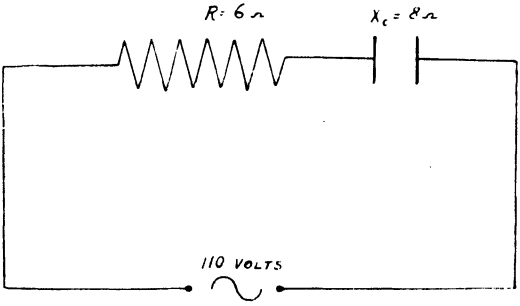


FIG. 94

Referring to the table of cosines, we find that the angle whose cosine is .6000 (or nearest this value) is 37°. Hence the phase angle is 37°.

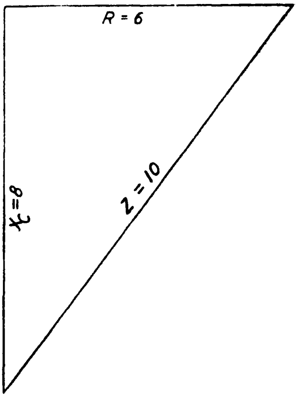


FIG. 95

Problem 2. Resistance and capacity reactance in series. See Fig. 94. Find I, if $E = 110$ volts.

Again the first step is to determine Z, either by the impedance triangle (Fig. 95) or by $Z = \sqrt{R^2 + (-X_C)^2}$. Then use

$$I = \frac{E}{Z}$$

If the capacity is given instead of the capacity reactance, then X_C can be first determined by the equation

$$X_C = \frac{1}{2\pi fC}$$

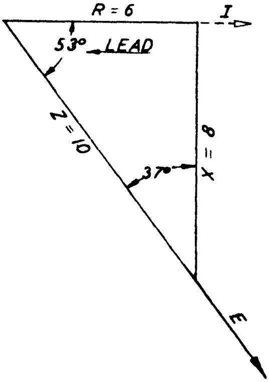


FIG. 96

Thus suppose $C = 332$ microfarads and $f = 60$. Change from microfarads to farads and proceed as before.

$$332 \text{ m.f.} = .000332 \text{ farads,}$$

and

$$X_C = \frac{1}{2 \times 3.1416 \times 60 \times .000332}$$

$$X_C = \frac{1}{.125}$$

$$= 8 \text{ ohms}$$

In all such circuits the current leads the voltage, and the angle of lead can be determined by the vector diagram (impedance triangle), by protractor or by calculation. Thus (Fig. 96), the phase angle between I and E is also the angle between *R* and *Z*. This angle has for its cosine

$$\frac{R}{Z}=\frac{6}{10}=.6$$

From the table the angle whose cosine is nearest 0.6, is 37°.

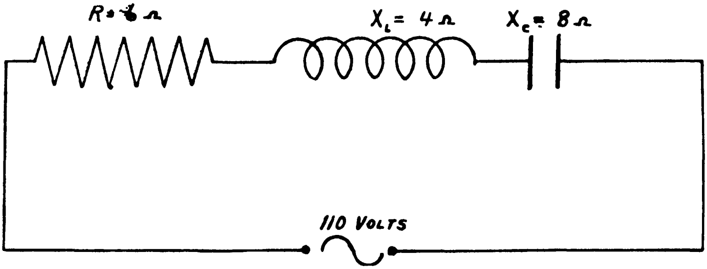


FIG. 97

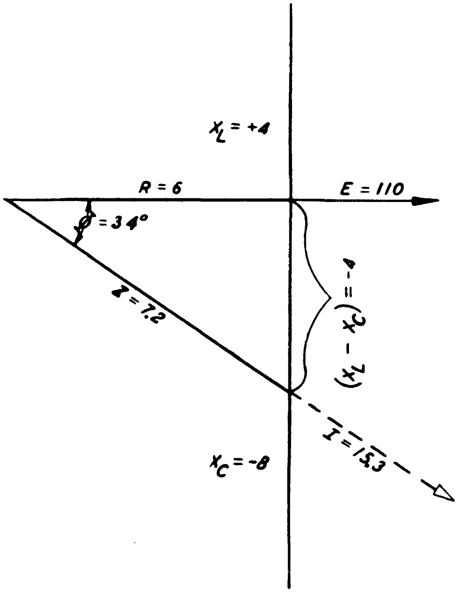


FIG. 98

Problem 3. Resistance, inductive reactance, and capacity reactance in series (Fig. 97). Given *E*, *R*, X_L, and X_C, to find *I*. Again we combine *R*, X_L, and X_C by the impedance triangle (Fig. 98). We find $Z = 7.2$ ohms and

$$I = \frac{E}{Z} = \frac{110}{7.2} = 15.3 \text{ amperes}$$

Moreover, in this impedance triangle we have included the vectors E and I to make the picture more complete. Note that I falls along the line Z, and E along the line R. This is always the case and makes it easy to determine the phase angle. It is the angle Φ (Greek letter pronounced like "fi"), in the picture. The cosine of angle Φ is

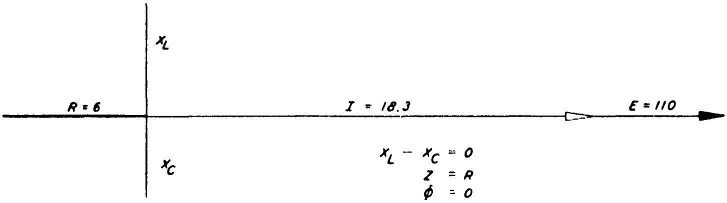


FIG. 99

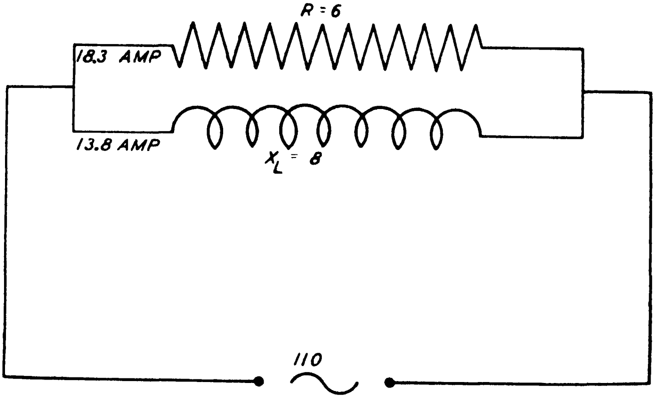


FIG. 100

$$\cos \Phi = \frac{R}{Z} = \frac{6}{7.2} = .8333$$

From the table we find that the angle Φ is approximately 56°.

Problem 4. Given E, R, X_L, and X_C to find I and Φ the phase angle, when X_L and X_C are equal. This problem is just like the preceding, except that X_L and X_C are now equal. Note that in this case X_L and X_C just offset each other's effects and that Z in this case is equal to R, and also that

$$I = \frac{E}{Z} = \frac{E}{R} = \frac{110}{6} = 18.3 \text{ amperes}$$

And note, too, that I is in phase with E, the phase angle Φ being zero. Because X_C and X_L just offset each other, this condition is called a condition of resonance, and such a circuit is called a resonant circuit. See vector diagram Fig. 99.

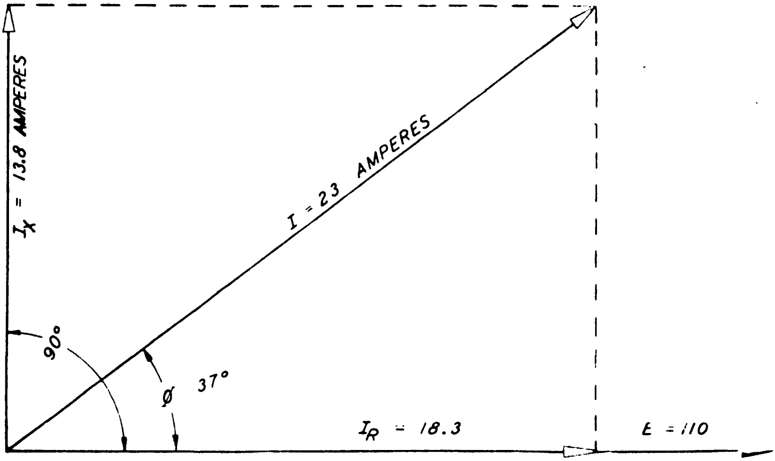


FIG. 101

Problem 5. R and X_L in parallel (Fig. 100). Given E, R, X_L to find I, Z, and Φ. Here the voltage 110 is impressed on each of the two branches—the reactance branch as well as the resistance branch. Hence we can calculate the current through each branch separately.

$$I_R = \frac{E}{Z_R} = \frac{110}{6} = 18.3 \text{ amperes}$$

$$I_X = \frac{E}{Z_X} = \frac{110}{8} = 13.8 \text{ amperes}$$

The line current is then the vector sum of these two branch currents. I_R is in phase with E, I_X is 90° behind E. Line I is

$$\begin{aligned} I &= I_R \oplus I_X \\ &= \sqrt{(18.3)^2 + (13.8)^2} \\ &= 23 \text{ amperes} \end{aligned}$$

The vector diagram is shown in Fig. 101. From it may also be found the phase angle Φ between line current I and line voltage E.

$$\cos \Phi = \frac{18.3}{23.0} = .7957$$

and from cos table $\Phi = 37°$

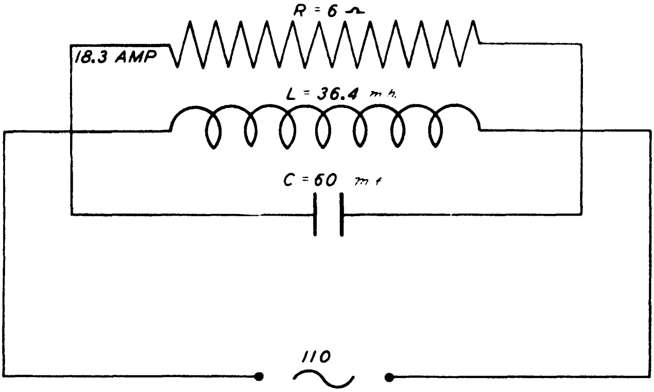


FIG. 102

Z the impedance for this circuit is now found by

$$Z = \frac{E}{I} = \frac{110}{23} = 4.8 \text{ ohms}$$

Problem 6. Given E, R, L, C to find I, Z, and Φ, if R, L, and C are in parallel. (Fig. 102.)

First find the separate branch currents from

$$I = \frac{E}{Z_R} \text{ and } I = \frac{E}{Z_X}$$

We do not know X_L and X_C but can find them (assuming the frequency to be 60 cycles per second).

$$\begin{aligned} X_L &= 2\pi f L \\ &= 2 \times 3.1416 \times 60 \times .0364 \\ &= 13.7 \text{ ohms} \end{aligned}$$

and

$$\begin{aligned} X_C &= \frac{1}{2\pi f C} = \frac{1}{2 \times 3.1416 \times 60 \times .000060} \\ &= \frac{1}{.0226} \\ &= 44.2 \text{ ohms} \end{aligned}$$

Then,

$$\begin{aligned} I_R &= \frac{E}{R} = \frac{110}{6} = 18.3 \text{ amperes} \\ I_L &= \frac{E}{X_L} = \frac{110}{13.7} = 8.0 \text{ amperes} \\ I_C &= \frac{E}{X_C} = \frac{110}{44.2} = 2.6 \text{ amperes} \end{aligned}$$

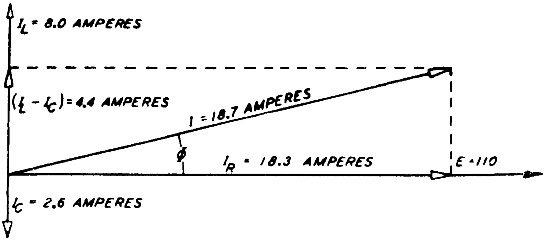


FIG. 103

These branch currents are now added as vectors to obtain the line current I. See Fig. 103. We can combine I_C and I_L first, since they lie in the same straight line and in opposite senses.

$$I_L \ominus I_C = 8.0 \ominus 2.6 = 5.4 \text{ amperes}$$

Then $$I_R \oplus (I_L \ominus I_C) = 18.3 \oplus 5.4 = 19.2 \text{ amperes}$$

Z can now be found by

$$Z = \frac{E}{I} = \frac{110}{19.2} = 5.74 \text{ ohms}$$

The angle Φ can be obtained from its cosine.

$$\cos \Phi = \frac{18.3}{19.2} = .9531$$

$$\Phi = 17.6^\circ$$

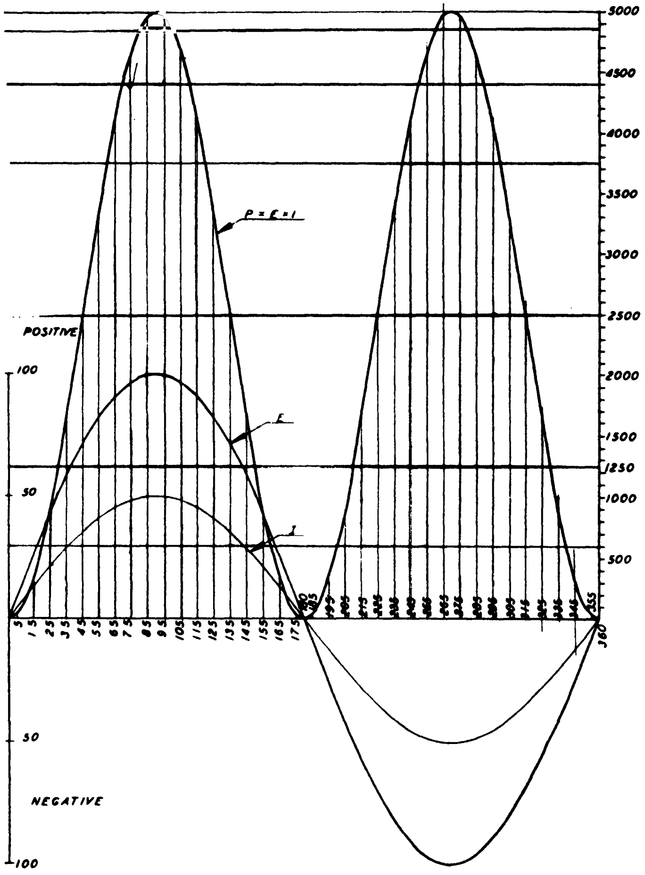


FIG. 104

24. POWER, POWER EQUATION:

In a D.C. circuit the power can be measured either by a wattmeter directly or by ammeter and voltmeter. In the latter case,

$$P = E \times I$$

In an A.C. circuit power can also be directly measured by a wattmeter. But it is not possible to measure power by use of a voltmeter and an ammeter except in the case when E and I are in phase. The reason will appear presently.

Let us assume a circuit in which current and voltage are in phase, and let us represent E and I by sine waves as in Fig. 104. Since E and I vary from instant to instant, the power during each cycle also varies from instant to instant. Using the equation

$$p = ei$$

we can plot the power curve shown in Fig. 104. Thus at the instant of maximum values, $e = 100$, $i = 50$ and

$$p = ei = 100 \times 50 = 5000$$

Similarly at the zero instants,

$$p = ei = 0 \times 0 = 0,$$

and so on for all points on the curves. If these various values of p are plotted we get a sine wave for the power, but both loops are positive, because both e and i are positive together, or they are both negative together, and in either case p is positive.

$$(+e) \times (+i) = +p$$
$$(-e) \times (-i) = +p$$

We have also learned that the reading of a voltmeter or ammeter is the effective value of a current or voltage. In other words, it is

$$E = .707\ E_{\max}$$
$$I = .707\ I_{\max}$$

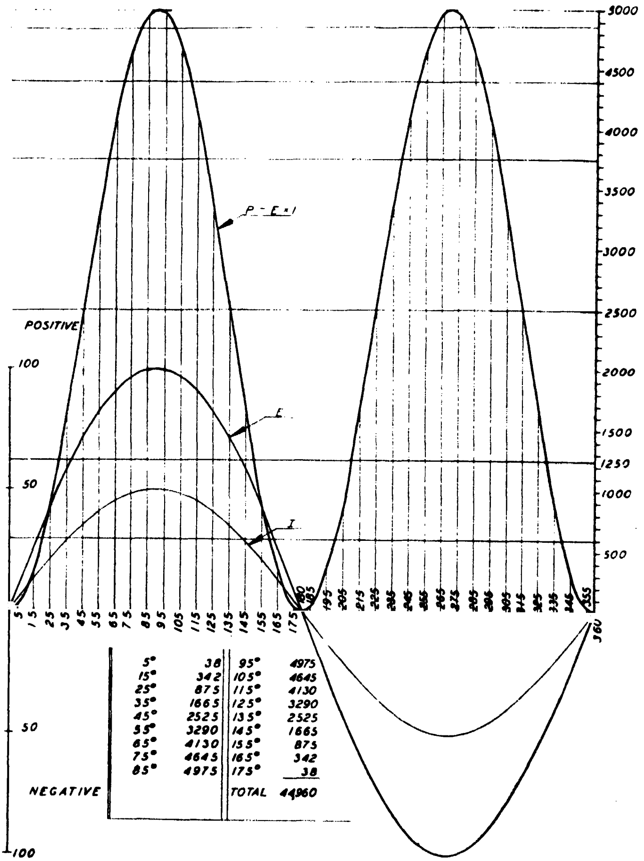
or $$E = .707 \times 100 = 70.7 \text{ volts}$$

and $$I = .707 \times 50 = 35.35 \text{ amperes}$$

So that if we multiply the voltmeter reading by the ammeter reading the power result would be

$$\begin{aligned} P &= E \times I \\ &= 70.7 \times 35.35 \\ &= 2499.2 \text{ watts} \end{aligned}$$

Now let us find the average power in one of the loops of the power curve in Fig. 104. This can be done by summing up the power for all the different instants during the half-cycle and dividing by the number of instants to get the average.



5°	38	95°	4975
15°	342	105°	4645
25°	875	115°	4130
35°	1665	125°	3290
45°	2525	135°	2525
55°	3290	145°	1665
65°	4130	155°	875
75°	4645	165°	342
85°	4975	175°	38
		TOTAL	44960

FIG. 105

Of course, the number of instants is so large that we can only approximate this by taking a good many, as is done in Fig. 105. Thus starting at 5° and taking an ordinate on the power curve, for each 10° interval up to 175°, we get the values shown. Adding these values we find a total of 44,960 watts, which divided by the number of ordinates or power intervals, 18, is

$$P_{ave} = \frac{44{,}960}{18} = 2498.3 \text{ watts}$$

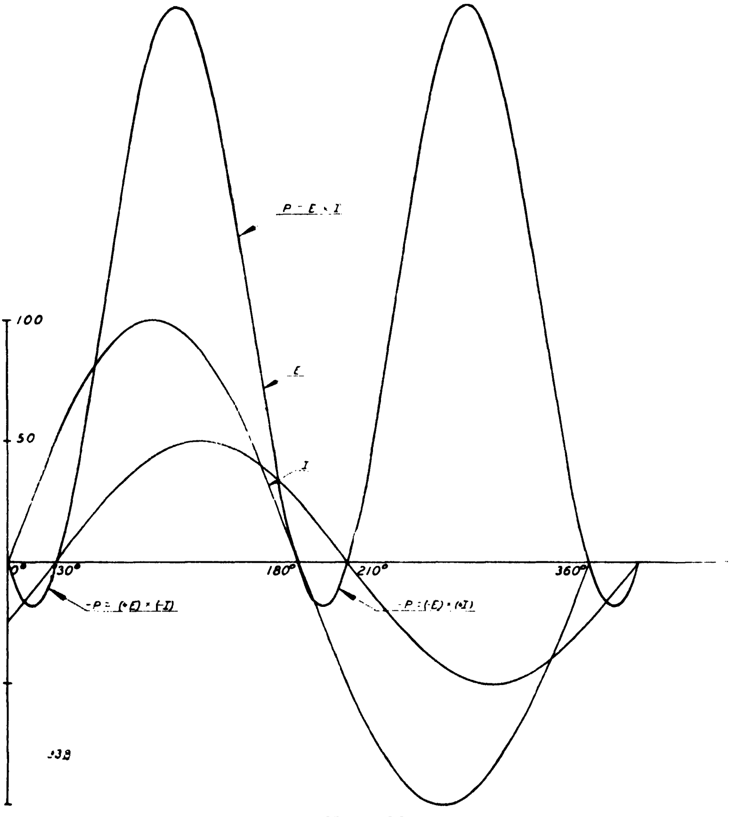


FIG. 106

The average power is of course what is read by the wattmeter. This approximates very closely the power as determined by multiplying the voltmeter and ammeter readings together, namely, 2,499.2 watts. Hence when E and I are in phase,

$$P = E \times I$$

just as in a D.C. circuit.

Assume, however, that E and I are out of phase by, let us say, 30°, and that I lags. Fig. 106 illustrates this. Then, as previously, plot the power curve, by using the instantaneous values of the power obtained by multiplying $e \times i$.

$$p = ei$$

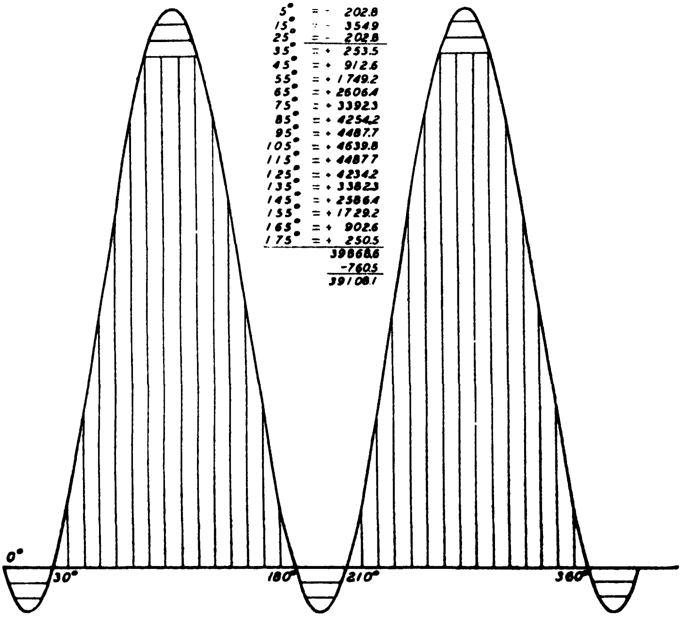


FIG. 107

Note now, that the power loops are irregular, in that there are two large loops (both positive) and two smaller loops (both negative). The negative power loops mean that the circuit gives back power instead of receiving it. They occur when e and i have opposite signs. That is, e is sometimes + while i is −, and vice versa. Then

$$(+e) \times (-i) = -p$$
$$(-e) \times (+i) = -p$$

Hence $-p$ is plotted below the line to form negative power loops. To get the average power, the negative loop must be subtracted from the positive loop, which is done in Fig. 106. That portion of the positive loop shaded by vertical lines represents the power during each half-cycle. If now we find the average value of this power loop as we did before, we obtain the results in Fig. 107. The sum total of these ordinates is 39,108.1 watts, which divided by the number of ordinates taken, 18, is

$$P_{\text{ave}} = \frac{39108.1}{18} = 2172.7 \text{ watts.}$$

In other words, using the same current, 50 amperes, and the same voltage, 100 volts, as before, we now find the average power to be 2,172.7 watts (and this is what the wattmeter will read), as against 2,500 watts when the current is in phase with the voltage. The fact that the two are out of phase by 30°, is responsible for the negative power loops in one power curve, and this in turn has decreased the power taken by the circuit. Let us compare these two values of power, namely, the value obtained by voltmeter and ammeter readings multiplied, and that read by the wattmeter.

$$P \text{ (by wattmeter)} = 2172.7 \text{ watts.}$$
$$P \text{ (by voltmeter-ammeter)} = E \times \text{I} = 2500 \text{ watts}$$

E and I both being effective values.

Then $$\frac{P \text{ (by wattmeter)}}{P \text{ (by voltmeter-ammeter)}} = \frac{2172.7}{2500}$$

or $$\frac{P}{EI} = \frac{2172.7}{2500}$$

$$\frac{P}{EI} = 0.866 \text{ (very nearly)}$$

from which $$P = E \times I \times 0.866$$

Note from the above that the wattmeter reading in the case just discussed (E and I out of phase by 30°) is equal to the product of the voltmeter reading, the ammeter reading the number .866. Now it is a peculiar coincidence that the number .866 happens to be the cosine of the angle 30°. The latter is the phase angle between E and I in our problem. So it would seem that in a circuit in which E and I are out of phase, the wattmeter reading, or the real power taken by the circuit, will be the product of the voltage, the current, and a third factor which is the cosine of the phase angle. Hence the power equation for such a circuit is

$$P = E \times I \times \cos \Phi^\circ.$$

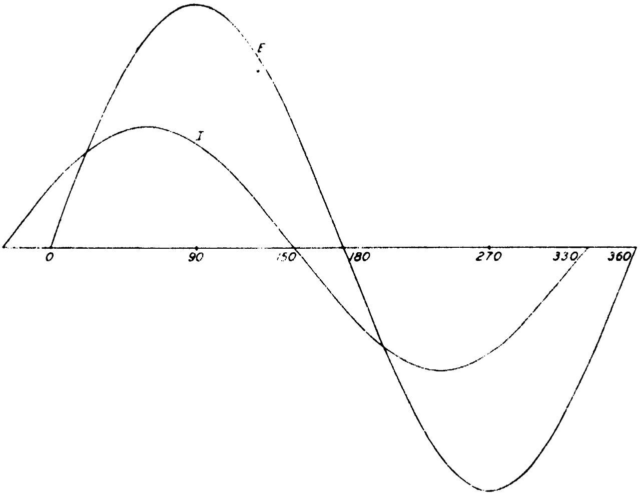


FIG. 108

Let us try this out in the former case in which E and I are in phase. The angle Φ in this case is zero. The power then should be

$$P = E \times I \times \cos 0^\circ.$$

$$P = 70.7 \text{ volts} \times 35.35 \text{ amps.} \times 1.00$$

The cosine of $0^\circ = 1.00$.

$$\text{Hence } P = 2499.25 \text{ watts}$$

This agrees with the value previously found and hence the above power equation also fits cases in which E and I are in phase. In fact, this equation is true for all alternating current circuits, except that later on we shall find it necessary to modify this equation slightly for polyphase circuits.

This equation holds also for circuits in which I leads E. For example, in Fig. 108 I leads E by 60°. In this case we can show by drawing the power curve and then averaging the ordinates as before that the average power during a cycle, as read by a wattmeter, equals

$$
\begin{aligned}
P &= E \times I \times \cos 60^\circ \\
&= 70.7 \times 35.35 \times .50
\end{aligned}
$$

since $\cos 60^\circ = 0.5$.
or

$$P = 1250 \text{ watts.}$$

Note that the phase angle Φ is larger than before, and so, too, would be the negative power loops. Hence there is actually less average power received and kept by the circuit than before.

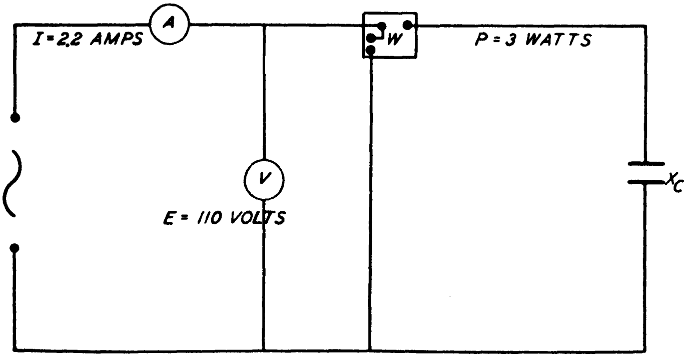


FIG. 109

25. POWER FACTOR:

We have just learned that in single-phase A.C. circuits

$$P = E \times I \times \cos \Phi$$

in which P is the real power as read by a wattmeter, I is the line current as read by an ammeter, and $\cos \Phi$ is the cosine of the phase angle between E and I. We also learned that this equation differs from the D.C. power equation by the factor cos Φ. This new factor is called the *power factor* of the A.C. circuit. When E and I are in phase, Φ is zero, and cos Φ is 1.00. The equation then becomes

$$P = E \times I \times 1.00$$

or

$$P = EI$$

which is the same as the D.C. power equation. E and I may be out of phase by an angle as large as 90° (theoretically at least). Thus in the circuit in Fig. 109, theoretically, the current in this condenser circuit leads by 90°. Hence the power should be zero ($\cos 90° = 0$).

$$\begin{aligned} P &= E \times I \times \cos \Phi \\ &= 110 \times 2.2 \times 0 = 0 \end{aligned}$$

As a matter of fact the power as actually measured by a wattmeter was 3 watts, which means that the phase angle was not quite 90°. We can find this phase angle from the power equation by solving for cos Φ. Thus,

$$P = EI \cos \Phi$$

$$\frac{P}{EI} = \cos \Phi$$

or

$$\cos \Phi = \frac{P}{EI}$$

and Φ is the angle whose cosine is $P \div EI$. Substituting the meter readings in this equation,

$$\begin{aligned} \cos \Phi &= \frac{3}{110 \times 2.2} = \frac{3}{242} \\ &= .0128 \end{aligned}$$

By reference to the cosine table we find angle Φ equal to approximately 89° 15′. If the 110 volts and the 2.2 amperes in this circuit had been in phase, the power would have been

$$\begin{aligned} P &= 110 \times 2.2 \times 1 \\ &= 242 \text{ watts} \end{aligned}$$

In this circuit, therefore, the power might vary between zero and 242 watts, all depending upon what the phase angle Φ is. This suggests that the power factor of a circuit is very important, particularly to the electric power company. Large currents can be supplied to consumers at the common commercial voltages, and yet if the power factor in an industrial plant is low (much less than 1.0) these large currents do not represent much power. Much smaller generating units, if able to supply smaller currents at high power factors (nearer 1.00) would be able to supply the customer with the proper amount of power and the power company would thus be saved money both on investment and in operation and upkeep.

Power factor being the cosine of Φ, the phase angle, it is always some number between 0 and 1.00, since the cosine is always between 0 and 1.00. The cosine is always expressed as a decimal, thus cos 30° = .866. Therefore power factor is usually spoken of as a percent. Thus, for circuits in which the phase angle is zero, we say the power factor is unity, 1.00, or 100%. If the angle is 30°, cos 30° = .866, we say the power factor is 86.6% or 87%. Power factors are considered excellent, if they reach a value 90% or more. Power factors of 80% and above are good. Power factors of 60% and below are considered very low.

26. KILOWATTS, KILOWATT-HOURS, KILOVOLT-AMPERES:

Power as measured by a wattmeter is expressed in watts or kilowatts. Our electric light and power bills are made out on the basis of "power used for a length of time," in other words, the average power times the number of hours. Hence the bill rendered is for the number of *kilowatt-hours* of energy consumed by the customer.

Alternators and transformers are rated in terms of *kilovolt-amperes*, not in kilowatts, and for a very good reason. Suppose we should rate an alternator at 50 kw. This is 50,000 watts. If the voltage rating is 230, the full load current capacity of the machine is 217.4 amperes. Now let us suppose that this generator is actually supplying 217.4 amperes at 230 volts to a consumer at 70% power factor. Then the power delivered to the customer is

$$\begin{aligned} P &= EI \cos \Phi \\ &= 230 \times 217.4 \times .70 \\ &= 35{,}000 \text{ watts} \\ &= 35 \text{ Kw.} \end{aligned}$$

In other words the machine has a power output of only 70% its rated capacity, yet it generates full-rated voltage and full-rated current. If under these same conditions the generator had to give the customer 50 kilowatts of power, it could do so only by running at an overload, as for example, by furnishing 310.6 amperes at 230 volts. Then the power delivered would be

$$\begin{aligned} P &= EI \cos \Phi \\ &= 230 \times 310.6 \times .70 \\ &= 50{,}000 \text{ watts or } 50 \text{ Kw.} \end{aligned}$$

To rate an alternator at 50 kilowatts would mean very little, therefore, since it is not certain that the alternator is to operate at unity power factor or any other power factor. Hence, an alternator is rated in kilovolt-amperes, which means

$$\text{Kilovolts} \times \text{amperes.}$$

In other words the alternator above would be rated as a 50 Kva. machine, since its voltage rating 230 volts × its current rating 217.4 amperes = 50,000 volt-amperes or 50 kilovolt-amperes. The manufacturer does not specify power output since he cannot foretell the power factor, but he does specify power output if the machine were used at unity power factor (or 100%). Similarly if a power factor of 80% were specified, the kilowatt rating in this case would be 40 Kw.

Another way of looking at this is through the equation for power

$$P = EI \cos \Phi$$

The product EI, or volt-amperes, is the power which *apparently* is delivered by the alternator. That is, 230 × 217.4 =

50,000 power units seem to be delivered, but because of a power factor of 70% only 35,000 watts *actually* are retained by the consuming equipment. The 35,000 watts are therefore the *actual* or *real* power, the true watts; the 50,000 volt-amperes are apparent power.

This can be pictured by vectors. If we use the voltage as a reference line, as in Fig. 110, we can show the real power, the apparent power, and a third vector, the reactive power (which shuttles back and forth between consuming equipment and the generator but does no real work). The angle Φ is 45° 30′. (See table of cosines, for a cosine = .70.) The real power, 35,000 watts, is shown in phase with the voltage vector E, where the current would be if it were in phase. I is shown 45° 30′ behind E, and the *apparent power* vector lies along the current vector. If we scale off the 35,000 and the 50,000 at this angle of 45° 30′, as shown, then the ends of these two vectors can be joined. This new line is ⊥ to the real power vector and is called the reactive power com-

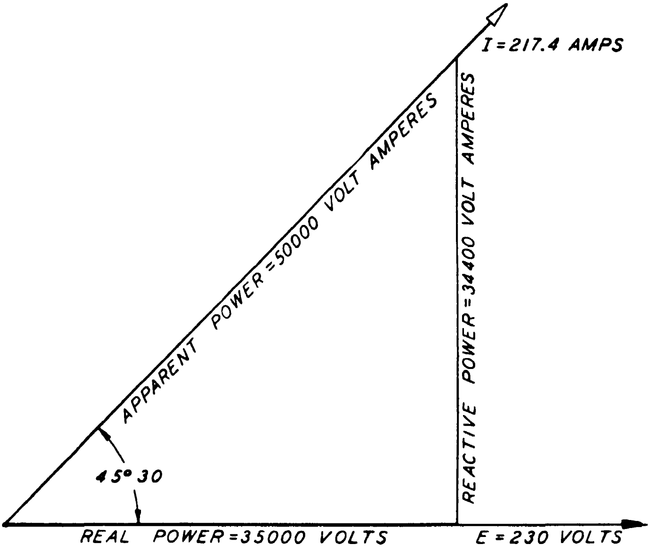

I = 217.4 AMPS
APPARENT POWER = 50000 VOLT AMPERES
REACTIVE POWER = 34400 VOLT AMPERES
45° 30
REAL POWER = 35000 VOLTS
E = 230 VOLTS

FIG. 110

ponent. It represents the power that shuttles back and forth between generator and load and does no useful work, merely serving to heat the conductors. The reactive component when added to the real power at 90° gives the total apparent power. The reactive power component can easily be found from the vector diagram. For example,

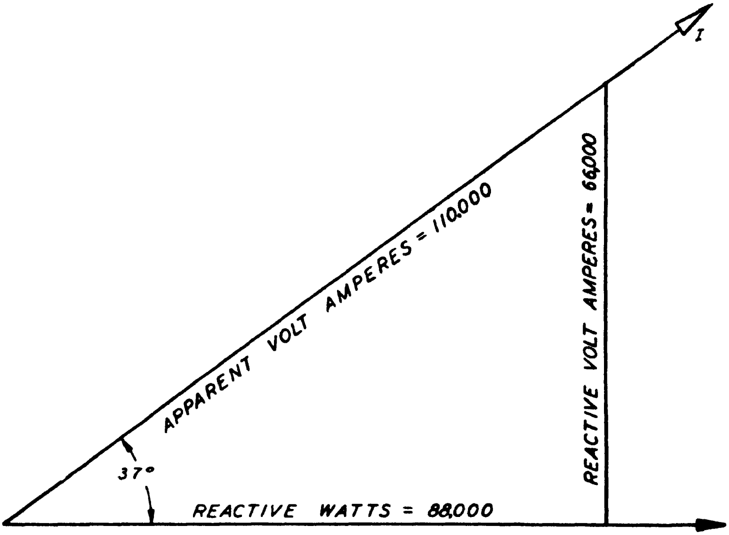

I
APPARENT VOLT AMPERES = 110,000
REACTIVE VOLT AMPERES = 66,000
37°
REACTIVE WATTS = 88,000

FIG. 111

Problem: Find the reactive power component and the real power in a circuit in which the line current is 500 amperes, the line voltage 220 volts, and the power factor 80% lagging. The real power is

$$\begin{aligned} P &= EI \cos \Phi \\ &= 220 \times 500 \times .80 \\ &= 88{,}000 \text{ watts} \end{aligned}$$

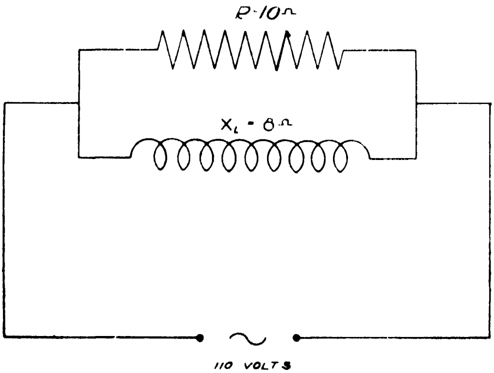
Now draw the vector picture as in Fig. 111.

$$\text{Since } \cos \Phi = .80$$
$$\Phi = 37^\circ \text{ (from cos table)}$$

Then E and I are 37° apart. The apparent power is $E \times I$ or $220 \times 500 = 110{,}000$ volt-amperes. Lay 88,000 watts off to scale along the vector *E*, and 110,000 volt-amperes along *I*, to the same scale. The ends of these vectors determine the reactive power component vector, which read off to the same scale is 66,000 volt-amperes.

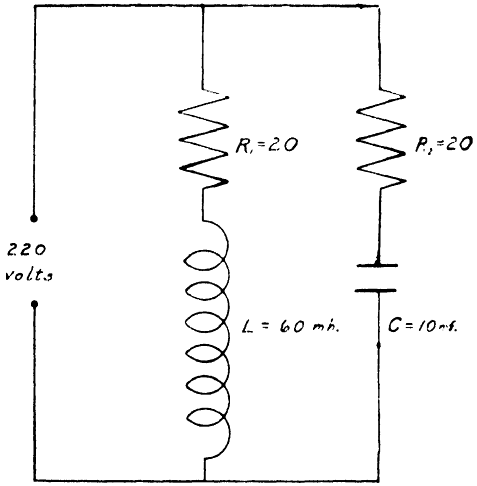
PROBLEMS—CHAPTER III

1. An electric iron draws a current of 5.5 amperes from the line when the voltage is 115 volts. What is the impedance of the iron? Does the impedance of an electric iron represent resistance, reactance, or the combined effect of resistance and reactance?
2. The heater of an electric mangle has an impedance of 13.5 ohms. What current flows when it is plugged onto a 115-volt line?
3. What current flows through two test lamps when testing the fuses on a 230-volt line (fuses being good) if the resistance of each lamp (hot) is 200 ohms?
4. A transformer coil is connected to the 220-volt supply line. R for the coil is 0.5 ohms, X_L for the coil is 15 ohms. What current flows through the coil, and at what phase angle? Is the current a leading or a lagging current?
5. A laboratory condenser takes a current of 2.2 amperes from a 60-cycle, 110-volt service. What is the capacity reactance of this condenser?
6. What is the inductance L, of the transformer coil in problem 4, assuming that its reactance was 15 ohms on a 60-cycle circuit?
7. What is the capacity of the condenser in problem 5?

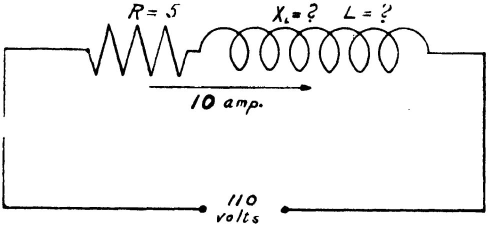


8. Find the branch currents and the line current in the circuit here pictured.

9. What is the impedance of the circuit in problem 8?
10. What would be the impedance and the line current if *R* and *X* in problem 8 were connected in series instead of in parallel?



11. Find the current in each branch, also the line current for the circuit shown in the accompanying diagram. Find also the total impedance of the circuit. The voltage is a 60 cycle voltage.



12. The circuit shown here is a 60-cycle circuit and the current is 10 amperes. What is the impedance of this circuit and what is the inductance of the coil in henrys?
13. What power is consumed by a carbon rheostat (non-inductive) when carrying an alternating current of 36 amperes, the pressure being 220 volts?

14. An inductive coil has an impedance of 10 ohms on a 60-cycle circuit. If connected to the 220 volt A.C. supply, what power does it consume, assuming the current to be 60° out of phase (lagging) with the voltage?
15. From the data in problem 14, draw the vector diagram and find R and X for the coil.
16. If the coil in problem 14 is joined in parallel with the rheostat of problem 13, across an A.C. voltage of 220, what is the total line current?
17. What is the total power consumed by the rheostat and coil together?
18. What is the phase angle between the line current and the line voltage in problem 16? What is the power factor of the circuit?
19. A single-phase induction motor takes a lagging current of 30 amperes on a 220-volt line. The angle of lag is 45°. Draw the vector diagram. Compute the power taken by the motor. If the motor is 80% efficient what is its H.P. output?
20. Complete the vector diagram called for in problem 19 by showing the true power input into the motor, the apparent power input, and the reactive or wattless component of power.
21. In order to improve the power factor of the line to which the motor in problem 19 is connected, a static condenser drawing 5 amperes at 220 volts, is connected in parallel with the motor. By vector diagram find the combined line current of motor and condenser, and determine the new phase angle. What is the improvement in power factor?
22. An alternator has a full load rating of 230 volts and 108.7 amperes. What is its Kva. capacity?
23. If the alternator in problem 22 supplies 50% of its full load current at 230 volts, and at a power factor of 87% what is its Kw. output?
24. If the alternator supplies a lighting load of 40 amperes, and an induction motor load of 60 amperes at a lagging angle of 37°, what is its total power output? What is its total current output and at what power factor?

CHAPTER IV

POLYPHASE CIRCUITS

27. SINGLE-PHASE CIRCUIT:

Up to the present we have considered only single-phase two-wire circuits. Only one A.C. voltage energizes a single-phase circuit, and usually, though not always, there are but two line wires. Fig. 112 illustrates such a circuit. A generator developing 110 volts supplies current to two lamps. Only one voltage is generated, and two wires are used. On the other hand, Fig. 113 also shows a single-phase circuit, but it is a three-wire single-phase circuit. Electric power is brought

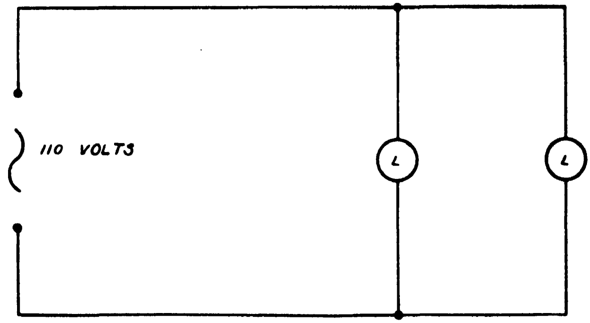


FIG. 112

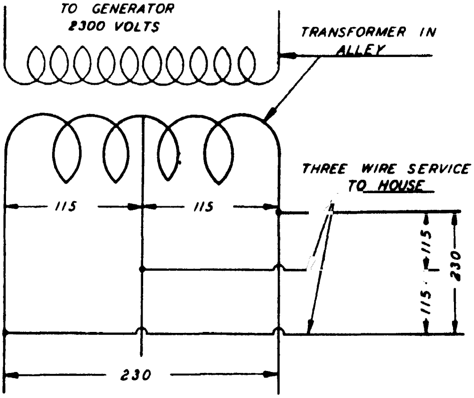


FIG. 113

to the home through a transformer mounted on a pole. Power comes to the transformer at 2,300-2,400 volts, and is taken out at 230-240 volts. Observe that a third wire is used here.

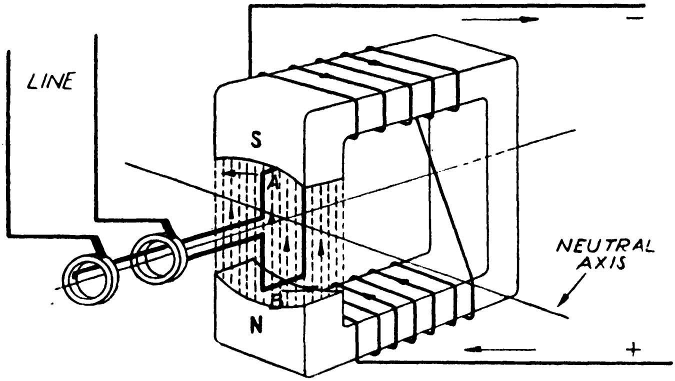


FIG. 114

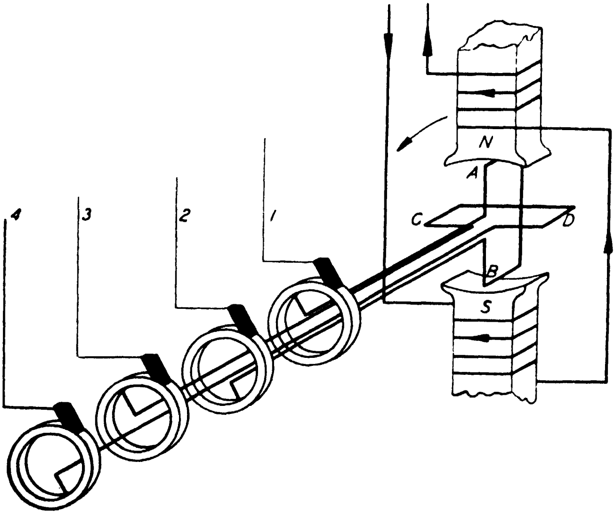


FIG. 115

It is brought out from the middle of the secondary coil of the transformer, and makes it possible to use only one-half of the 230 volts between the two outside wires, or 115 volts for lighting service. At the same time 230 volts is available for power purposes, such as for an electrical range in the home. In reality there is only one voltage source here, 230 volts. The two 115-volt voltages are merely the result of splitting the 230-volt voltage into two equal parts, by tapping the transformer coil at the middle and bringing out from this tap the third wire. This three-wire circuit is very much like a D.C. three-wire circuit.

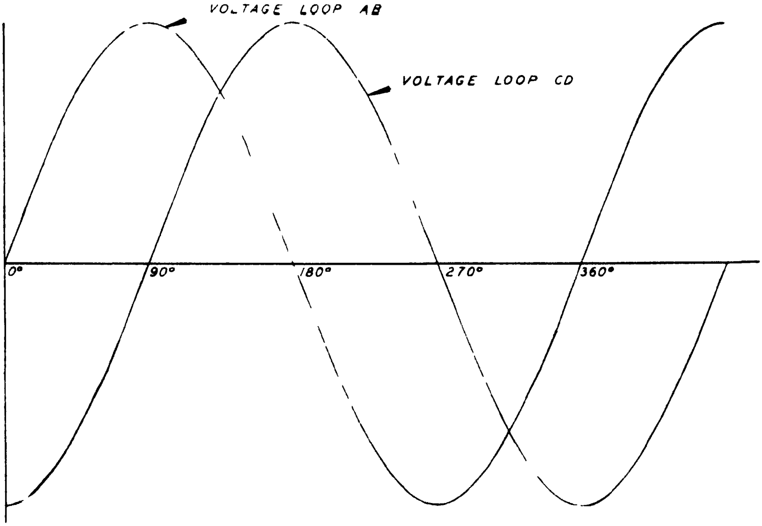


FIG. 116

28. TWO-PHASE CIRCUIT:

Refer now to Fig. 114, which illustrates a simple generator having a single rotating loop, the ends of which are connected to slip rings. Such a loop develops a sine wave of voltage. Suppose now we add another loop at right angles to the first and connected to two additional slip rings, as in Fig. 115. The loop *CD* as it rotates, also generates a voltage of sine wave shape. But, the loop *CD* reaches the neutral plane position, as well as the middle of the pole faces, out of step with the loop *AB*. The two loops have been placed in the machine 90° apart, and as they rotate they follow each other around always 90° apart. This is shown in Fig. 116. Here we have a simple generator capable of generating two distinctly separate voltages, one by each loop; the two voltages are equal; and they differ in phase by 90°. Through the slip rings these

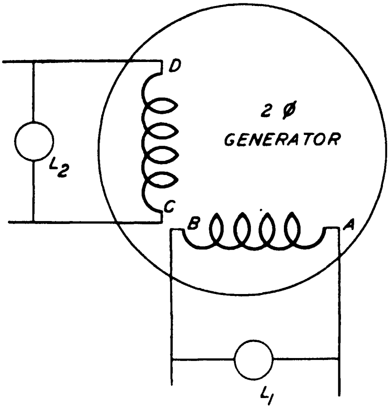


FIG. 117

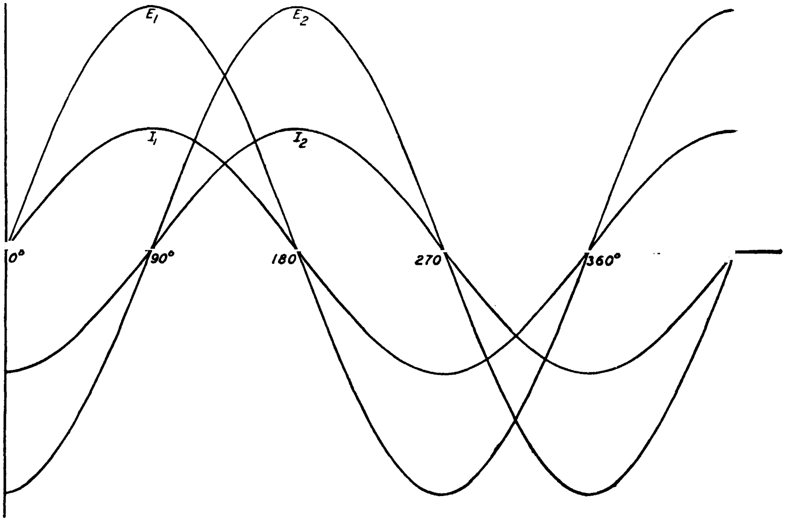


FIG. 118

voltages are brought out to four line wires. Line wires 1 and 2 supply current to a lamp L_1, and line wires 3 and 4 supply current to a lamp L_2. This arrangement constitutes a two-phase circuit. The generator is a simple two-phase generator. We can picture this arrangement by using symbols as in Fig. 117. The coils *AB* and *CD* are drawn at right angles to indicate that the voltages they generate are 90° apart. Coil *AB*, lamp L_1, and line wires 1, 2 constitute a single-phase circuit. Coil *CD*, lamp L_2, and the line wires 3, 4 constitute another single-phase circuit. The two together constitute a two-phase circuit. If the two circuits are alike, as they are above, then not only are the two voltages 90° apart, but so, too, are the two currents in these circuits. See Fig. 118.

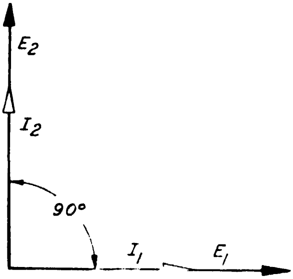


FIG. 119

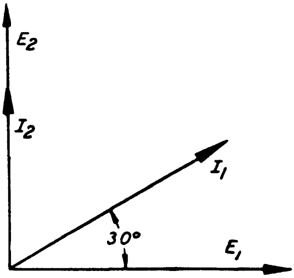


FIG. 120

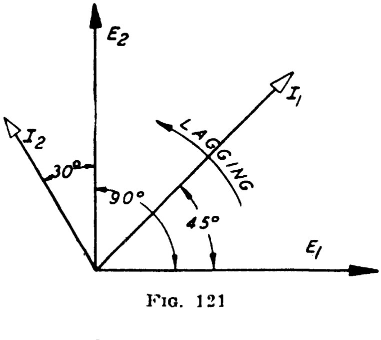


FIG. 121

And of course, such an arrangement also has its vector picture as in Fig. 119 which shows both voltages and both currents. Moreover, the currents I_1 and I_2 need not be in phase with their respective voltages E_1 and E_2. Thus (Fig. 120), I_1 lags behind E_1 by 30°, while I_2 is in phase with E_2. This would be the case if we should replace the lamp L_1 (Fig. 117) by a single-phase motor which would have a lagging power factor. In Fig. 121, both currents are lagging behind their voltages which would be the case if both circuits contained inductive load.

We are discussing here a two-phase voltage and a two-phase current, as developed in a simple machine consisting of two separate loops *AB* and *CD*. In the actual machine, of course, there are many coils joined in series instead of single loops. But the turns in one group are so spaced around the stator iron as to be 90° electrically out of phase with the turns in the other group.

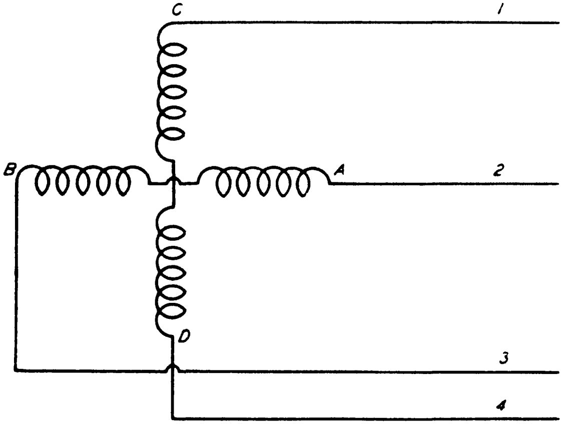


FIG. 122

The two-phase four-wire arrangement shown above is sometimes represented as in Fig. 122. The two phases are not electrically connected.

29. TWO-PHASE THREE-WIRE CIRCUIT:

Recall that in the two-phase circuit just discussed, four line wires were used to the two loads. It is possible to use only three wires to supply these loads and thus effect a saving in copper. Fig. 123 illustrates this. The two coils *AB* and *CD* are electrically connected at the generator, *B* and *C* being joined, and the line wires from points *B* and *C* are now replaced by a single line wire, making only three all told. Suppose each coil generates 100 volts. Then between lines 1 and 2, also between lines 2 and 3, the voltage is 100 volts. Between the outside line wires 1 and 3, the voltage is not 100 but 141.4 volts. This is because lines 1 and 3 include both phases, and

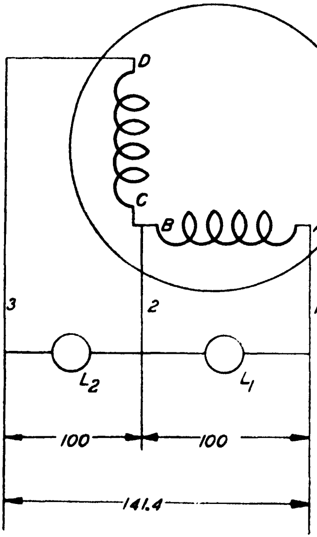


FIG. 123

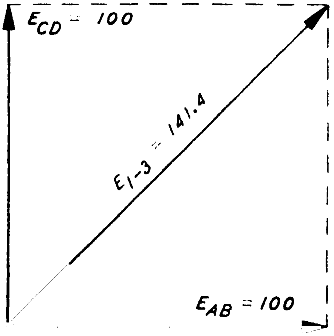


FIG. 124

therefore the voltage from line 1 to line 3 must be the vector sum of the voltages of the two phases. Or

$$E_{1\text{-}3} = E_{AB} \oplus E_{CD}$$

But the two-phase voltages are at 90°. Hence by vectors (Fig. 124), the voltage across the outside lines is 1.414 times the voltage of either phase. The number $1.414 = \sqrt{2}$. Hence the above statement can be written

$$E_{1\text{-}3} = \sqrt{2} \quad E_{\text{phase}}$$

Let us further assume that the current taken by L_1 and L_2 is 10 amperes each. Then phase *AB* delivers 10 amperes to L_1 and phase *CD* delivers 10 amperes to L_2, both currents, of course, passing through the common middle wire. This middle wire carries two 10 ampere currents, which are out of step with each other. In the case of the lamps L_1 and L_2, these currents are 90° apart. The vector sum of these currents is the current in the middle or common wire. Thus

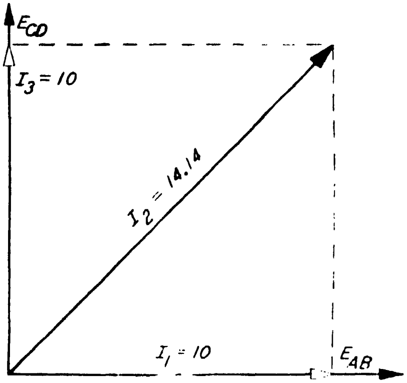


FIG. 125

(Fig. 125), *I* in line wire 1 is 10 amperes, I_3 in line wire 3 is 10 amperes, and I_2 in line wire 2 is

$$\begin{aligned} I_2 &= I_1 \oplus I_3 \\ &= 10 \oplus 10 \\ &= 14.14 \text{ amperes} \end{aligned}$$

Or again, in a two-phase circuit such as this, the middle line current is

$$I \text{ (common wire)} = \sqrt{2} \times I \text{ (outside wire)}$$

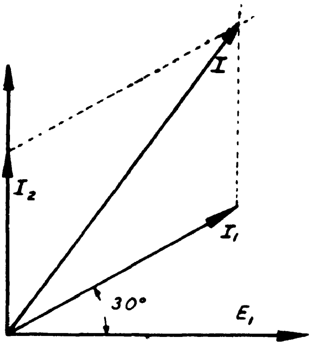


FIG. 126

If, however, I_1 and I_3 are not 90° apart as would be the case in a problem such as pictured in Fig. 120, which is repeated here in Fig. 126, the common wire current is not

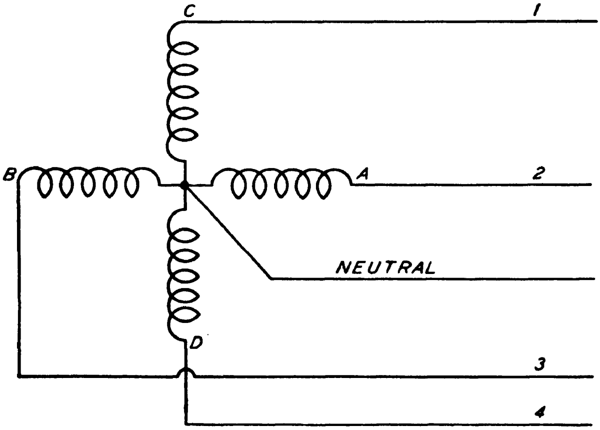


FIG. 127

$\sqrt{2}$ times the current in the outside line. But it is the vector sum at 60° as shown, and is in this case equal to 17.3 amperes. The middle line wire must evidently be a larger size wire than either outside wire, since it may carry a much larger current. It is not correct to call this middle wire a *neutral wire.*

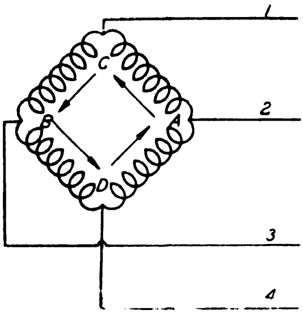


FIG. 128

30. OTHER TWO-PHASE ARRANGEMENTS:

The two-phase three-wire circuit is easily unbalanced both as to current and voltage values. Other arrangements of the two-phase system are at times more desirable. Thus in Fig. 127, the four-wire arrangement of the two phase becomes a five-wire arrangement. A fifth wire is brought out from the neutral point or middle point of the two phases. In this case

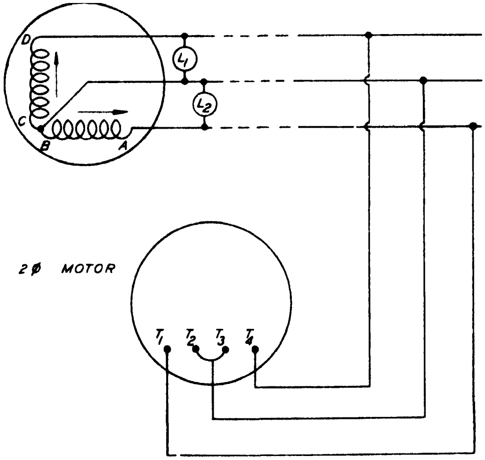


FIG. 129

the two phases are electrically connected at their mid-points. So long as the currents in the two phases remain balanced, no current flows in the neutral wire. This arrangement is sometimes called a "star" two-phase arrangement, either for four-wire or for five-wire circuits, to distinguish it from the "mesh" two-phase arrangement shown in Fig. 128. Here all coils are joined in one continuous series and line wires 1, 4, (phase *AB*), and 2, 3, (phase *CD*) are taken at points diametrically opposite each other. The current in each line wire equals $\sqrt{2}$ × the current in the phase.

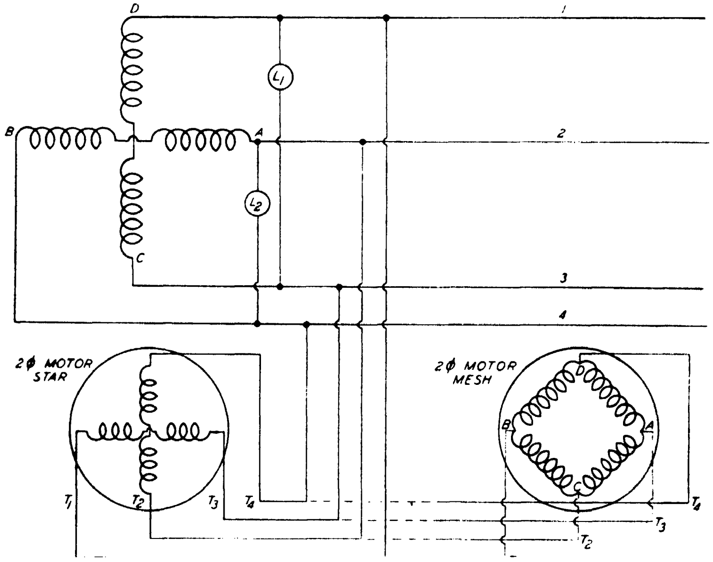


FIG. 130

31. TWO-PHASE LOAD CONNECTIONS:

We have concerned ourselves thus far only with the generator end of two-phase circuits. What are the load connections? Assume a three-wire two-phase circuit as in Fig. 129, a four-wire circuit as in Fig. 130, and a five-wire circuit as in Fig. 131. Single-phase loads may be connected independently of one another as shown in the several illustrations. In the five-wire circuit, however, they are connected between a line wire and the neutral.

The load may itself, however, be of two-phase character. Thus, it may be a two-phase motor, in which case all four line wires are joined to the four motor terminals. Or two motor terminals are connected together and the middle wire of the two-phase three-wire line joins this common connection. See illustrations.

The load may be two-phase star or mesh, just as the source, as is shown in the figures.

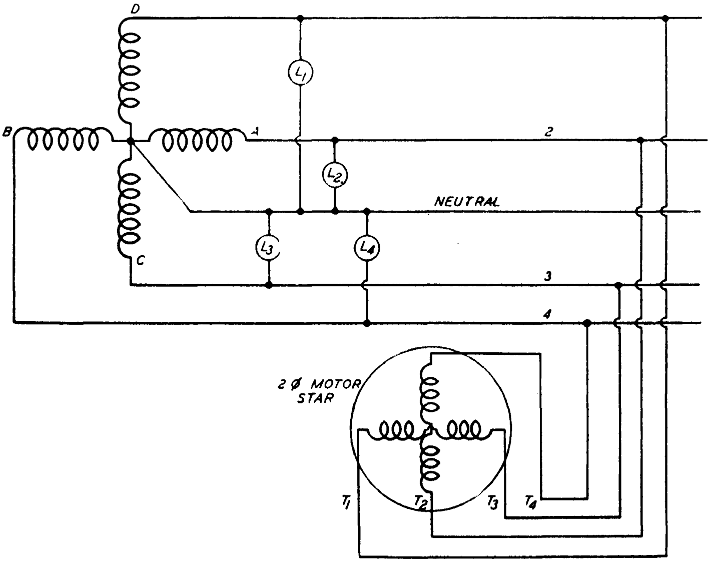


Fig. 131

32. CHOICE OF POLYPHASE SYSTEMS:

In general, the trend has been, and is now, toward the use of three-phase systems. There are very good reasons for this choice. Single-phase power is pulsating, that is, during one cycle we get two instants of maximum power, these instants coming at 180° E. intervals. Also we get at least two instants of zero power. This means non-uniform power flow. In a two-phase circuit (also four-phase) we get four instants of maximum power at 90° intervals. In a three-phase circuit we get 6 instants of maximum power, coming at intervals of 60°. The three-phase circuit represents a smoother power flow, just as the eight-cylinder gas engine produces a smoother flow of power than does a six-cylinder or a four-cylinder engine.

Moreover, given a definite machine (pounds of copper, plus pounds of iron, etc.), the capacity of the machine when arranged for a three phase is about 50% greater than when connected for single phase, and about 6% greater than when connected for two phase.

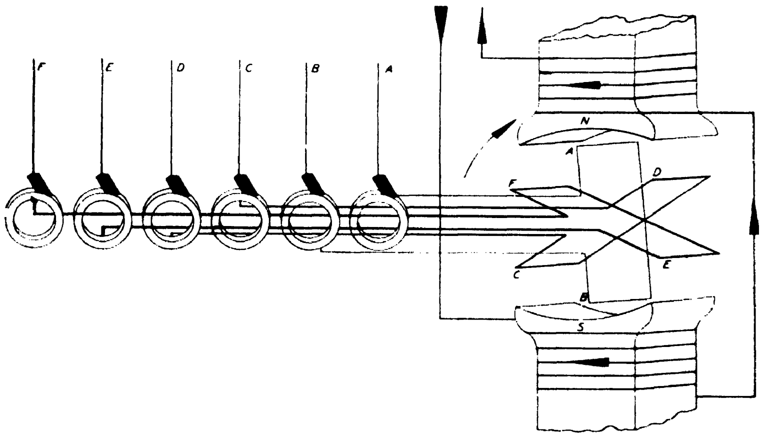


FIG. 132

Again, the copper requirements of a three-phase circuit are approximately 25% less than for a single-phase circuit.

Three-phase motors are cheaper and more rugged than single-phase motors and deliver at the pulley a more uniform power to the connected load than do either single or two-phase motors. Three-phase motors offer no starting difficulties, such as single-phase motors offer. And further, three-phase transmission systems are more economical and afford better voltage regulation than do the other systems.

Single-phase and two-phase equipment are still in use, and will probably continue in use, although the latter is gradually being replaced by three-phase units. Single-phase equipment is becoming limited to definite kinds and sizes. Thus, in some communities single-phase motors up to 15 H.P. capacity are permitted, but not more than this.

33. THREE-PHASE SYSTEMS:

Instead of using two loops at 90°, such as was done in the simple two-phase generator, let us use three loops 120° apart as in Fig. 132. Each loop generates its own sine wave of voltage. Hence this simple generator develops three separate voltages, reaching their peak values at 120° intervals. See Fig. 133. Observe that the three loops have their ends connected to slip rings, six in number. If line wires were connected to these slip rings, each loop could act as a single-phase generator supplying its own single-phase circuits through two line wires. This would require six line wires. Three-phase systems in common use require only three or four wires.

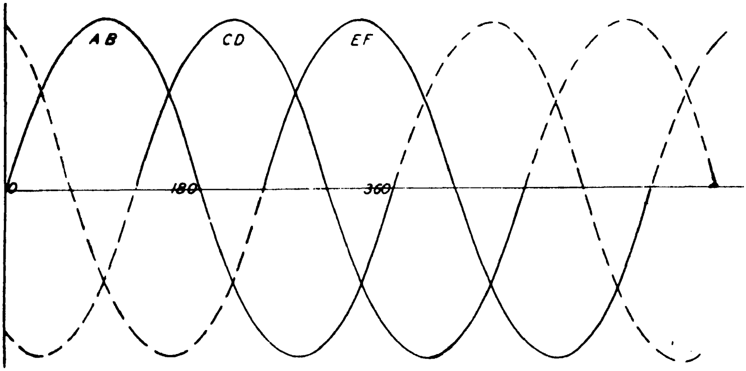


FIG. 133

34. THREE-PHASE STAR OR Y-CONNECTION:

The six terminals *A*, *B*, *C*, *D*, *E*, *F*, of the elementary generator in Fig. 132 are ordinarily not available outside the frame of the machine, except perhaps in the case of laboratory generators. Ordinarily these ends are connected inside the machine in one of two very definite ways, and three or four wires are brought out through the frame for connection to the outside circuit. These two methods of connection are called the "star" or Y and the "mesh" or delta (△). We will consider each in turn.

Consider the three loops *AB*, *CD*, and *EF*, rotating past the *N* and *S* poles, in a counter-clockwise direction. At the instant shown in Fig. 130, loop *AB* has reached the middle of the pole faces. *CD* will reach this position 120° E. later and *EF* will follow 120° E. behind *CD*. Note the order in which these loops rotate past the poles: *AB*, *CD*, *EF*. This order of rotation or of reaching a given position while rotating is

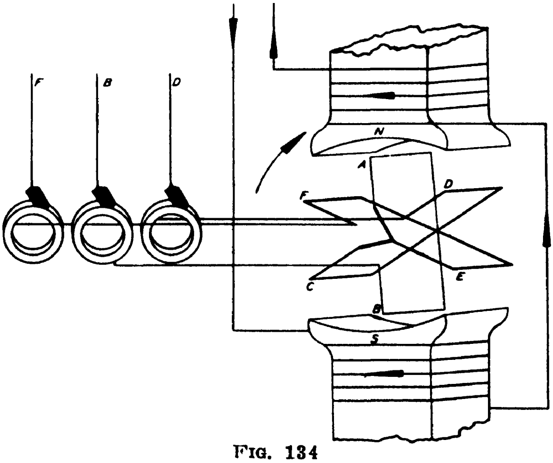


FIG. 134

called "phase rotation" or order of rotation of the phases. If the loops be made to rotate in the clockwise direction this order of phase rotation is changed and becomes *AB*, *EF*, *CD*. This is an important point to remember.

Another point to be noted is that the side *A* of loop *AB*, is 120° E. ahead of side *C* of loop *CD;* also side *C* is 120° E. ahead of side *E* of loop *EF*. This is important, because side *C*, for example, is only 60° away from side *F* of loop *EF*.

For a correct three-phase voltage, it is necessary that the three voltages generated be 120° apart. If *A* is assumed to be the start of phase *AB*, *C* must be the starting-end of phase *CD*, and *E* must be the start of phase *EF*. Also *B*, *D*, and *F* must be the finishing ends of the three phases respectively.

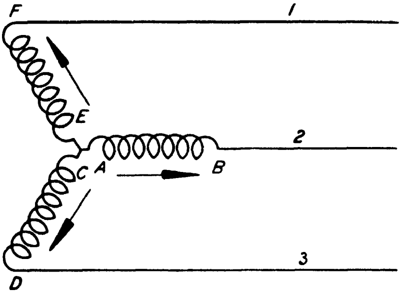


FIG. 135

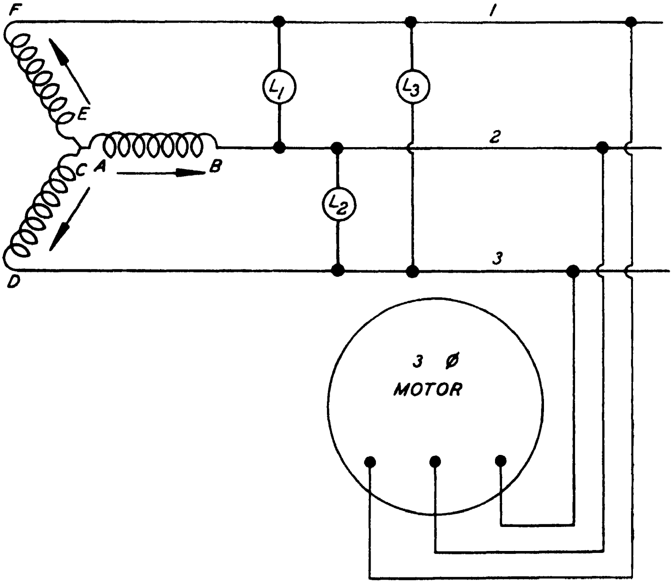


FIG. 136

Suppose now we connect together, inside the machine, three of these six ends, let us say, the three starting ends, as shown in Figs. 134, 135. Then the finish ends *B*, *D*, *F*, are free to be brought out to the line wires 1, 2, 3. Here we have a means of developing a three-phase voltage, to be brought to the load by only three line wires. Moreover, either single-phase, or three-phase loads may be connected to these line wires. See Fig. 136. If single-phase loads are connected, they should be evenly distributed among the three pairs of line wires, 1-2, 2-3, 3-1, so as to keep the circuit "*balanced.*" Three-phase loads such as motors are ordinarily by their very nature "balanced." The phases are built alike, hence draw like currents and need only three terminals for connection to a three-phase three-wire line.

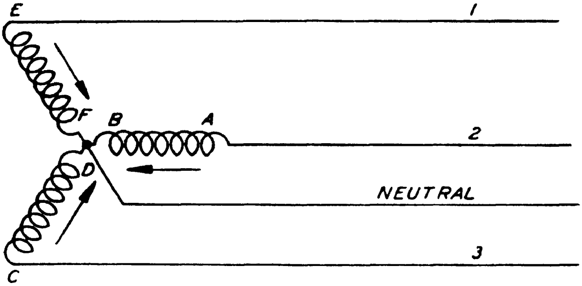


FIG. 137

The type of three-phase connection of the loops *AB*, *CD*, *EF* here discussed is called the star, or Y connection, and is somewhat more common than the other type, known as delta. Instead of connecting *A*, *C*, and *E* together, the finish ends, *B*, *D*, and *F* could have been joined in common, and then ends *A*, *C*, and *E* would be brought out to the line wires, with the same result, as shown in Fig. 136.

Sometimes a fourth wire is used in the three-phase star circuit. The common junction of the three starting or three finishing ends of the phases is called the neutral point. A fourth line wire may be brought out from this point, as in Fig. 137. Single-phase loads are connected from any outside line wire to the neutral; three-phase loads to the three line wires. The load itself may also have a neutral point and the neutral line would run to this point. See Fig. 138. The four-wire system is not as commonly used as the three-wire either for star or delta three-phase circuits.

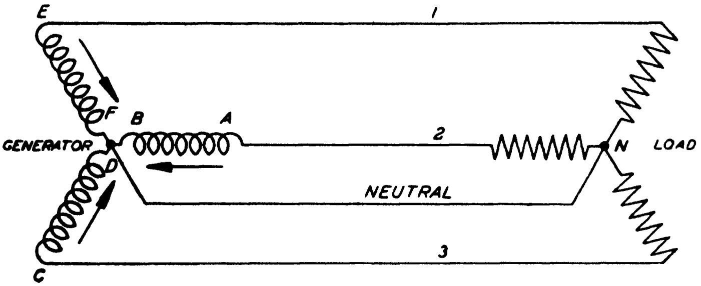


Fig. 138

35. THREE-PHASE DELTA (Δ) OR MESH CONNECTION:

Refer again to the simple three-phase generator pictured in Fig. 132. The six ends of the three phases are *A*, *B*, *C*, *D*,

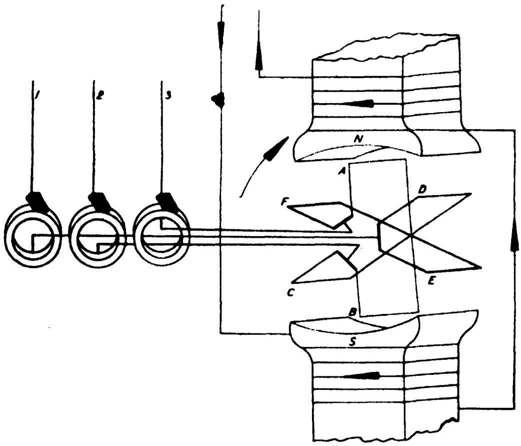


Fig. 139

E, *F*. Suppose now we join the three coils in series fashion, as shown in Figs. 139, 140. Note that "series fashion" means that the finishing end of phase *AB* is connected to the start-

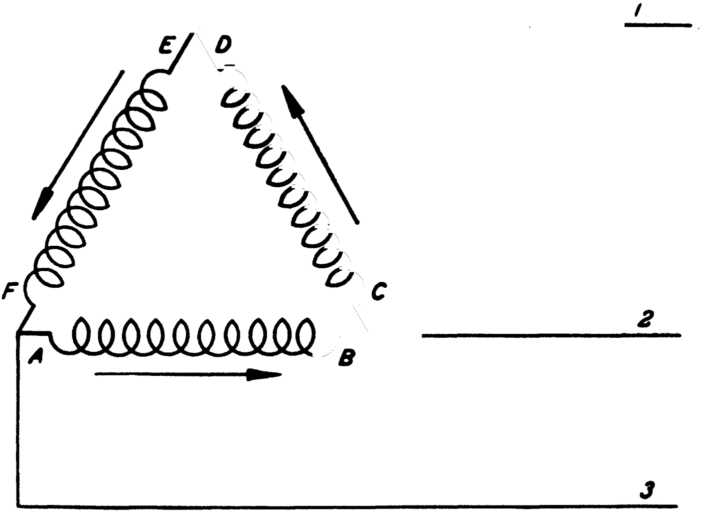


FIG. 140

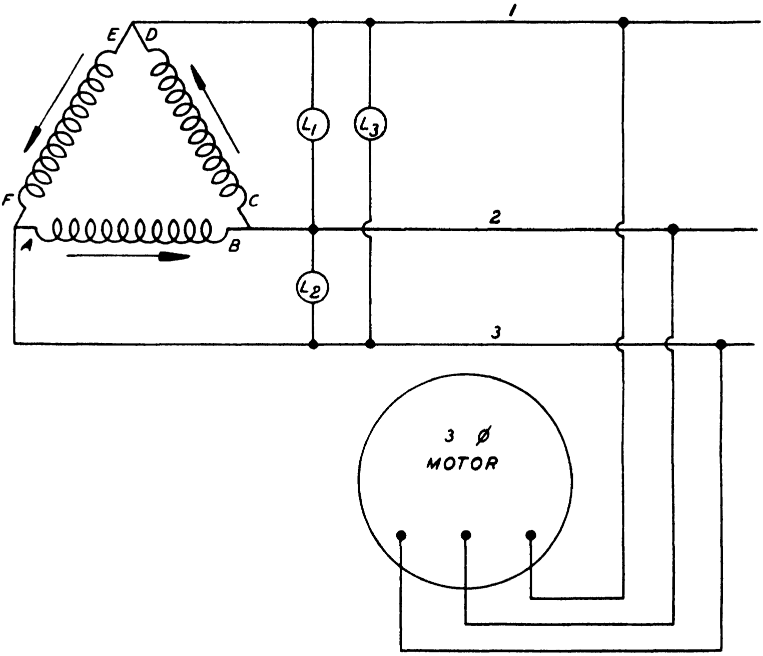


FIG. 141

ing-end of *CD*, or end *B* is joined to end *C;* the finishing-end of phase *CD* is joined to the starting-end of *EF*, or end *D* is connected to end *E;* similarly *F* and *A* are joined. From these three junction points we pass through the slip rings to the line wires. This is the three-phase delta connection.

The essential difference between star and delta connections is this: star connection means three starting- (or finishing-) ends of phases connected together in a common point (neutral); delta connection means the starting-end of one phase connected to the finishing-end of the preceding phase, in continuous series fashion, so that a closed series circuit results.

As in the case of the star connection, either single-phase or three-phase loads may be connected in a delta circuit as shown in Fig. 141.

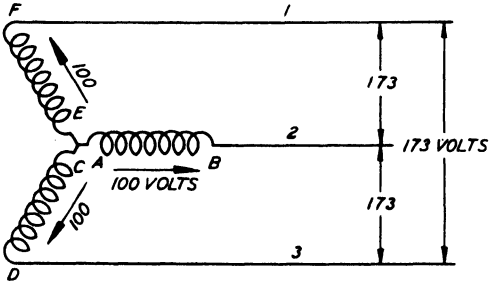


FIG. 142

36. THREE-PHASE VOLTAGE RELATIONS:

In a three-phase star circuit, the voltage between two line wires (not neutral) is $\sqrt{3} \times$ the voltage per phase. In a three-phase delta circuit the line voltage equals the phase voltage.

Refer to Fig. 142. Here we have a star circuit. Each phase generates 100 volts. Observe that the arrow points from *A* to *B*, *C* to *D*, and from *E* to *F*. *A*, *C*, and *E* are the starting-ends, *B*, *D*, and *F* are the finishing-ends of the phases. According to the statement at the beginning of this section the voltage between any two line wires should be $100 \times \sqrt{3} = 100 \times 1.73 = 173$ volts. Let us show that this is true. We are to find, for instance, the voltage E_{1-2} between line wires 1 and 2. Now this voltage is the result of the voltages generated by phases *AB*, and *EF*, since these two phases lie between line wires 1 and 2. See Fig. 143, which

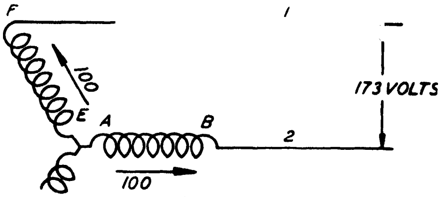


FIG. 143

shows only lines 1, 2, and phases *AB*, *EF*. Evidently, the voltage between line wires 1 and 2 is the vector sum or the vector difference of the two phase voltages *AB* and *EF*. We must determine whether these two must be added or subtracted vectorially.

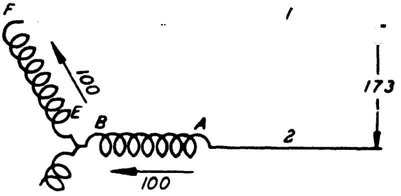


FIG. 144

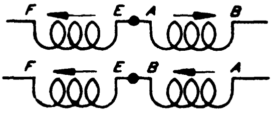


FIG. 145

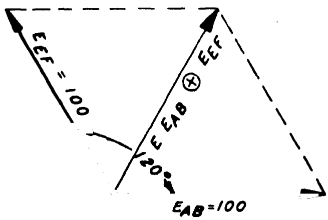


FIG. 146

Suppose the two phases *AB*, *EF* had been joined in series by connecting the finishing-end *B* to the starting-end *E* instead of as in Fig. 144. Comparing these two connections as in Fig. 145, we find that in the one case the two arrows point oppositely, and in the other case the two point in the same sense. In the latter case, we have evidently a case of addition of vectors, since the arrows point in the same way. Hence the two voltages would in this instance be added as in Fig.

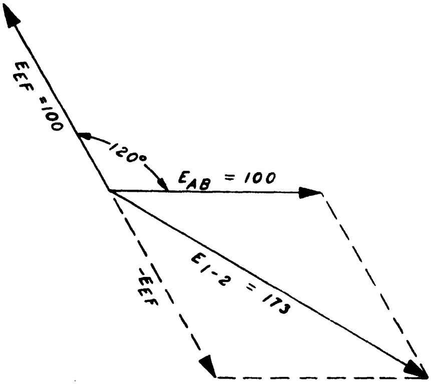


FIG. 147

146, the angle being 120°. But in the case of our correct star connection (start connected to start) we have a connection like the upper part of Fig. 145, where the arrows point in opposite senses. Hence in the star circuit the line voltage is the result of a "subtractive" series connection, and E_{1-2} must be the vector difference between E_{AB} and E_{EF}, as shown in Fig. 147. This shows that E_{1-2} equals 173 volts. In like manner E_{2-3} is the vector difference between the phase voltages E_{CD} and E_{AB}; also E_{3-1} is the vector difference between E_{EF} and E_{CD}. These are vectorially combined in Figs. 148 and 149.

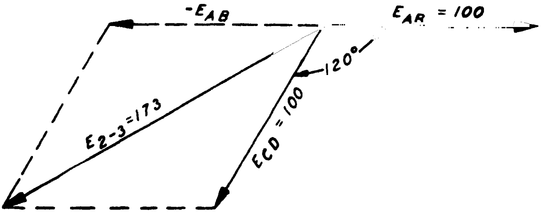


FIG. 148

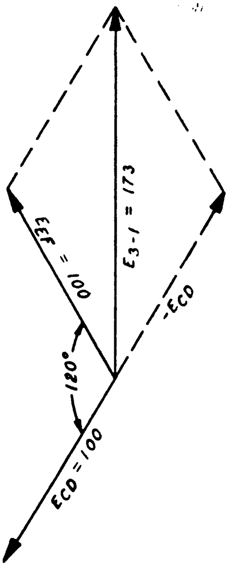


FIG. 149

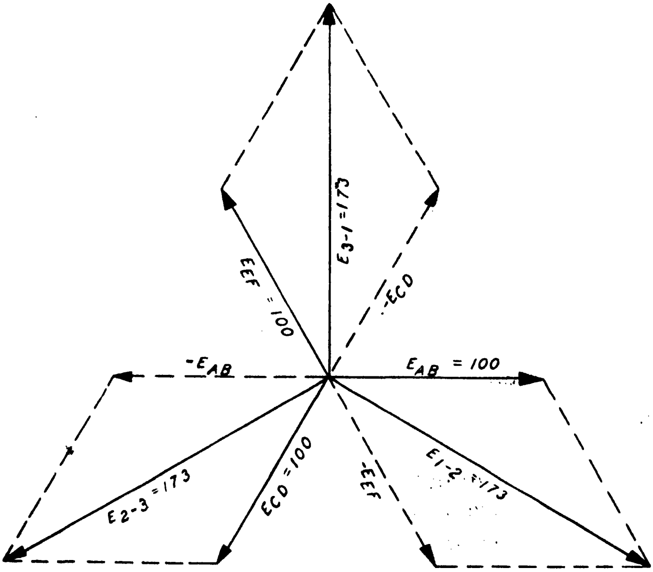


FIG. 150

Note, in the above, two things: (1) the importance of properly identifying the start and the finish of each phase, because of the fact that interchanging the two ends actually means reversing the phase and the voltage; (2) the three vector pictures show the three-phase voltages and the three line voltages at 120°. The three may be combined in a single vector picture, as in Fig. 150.

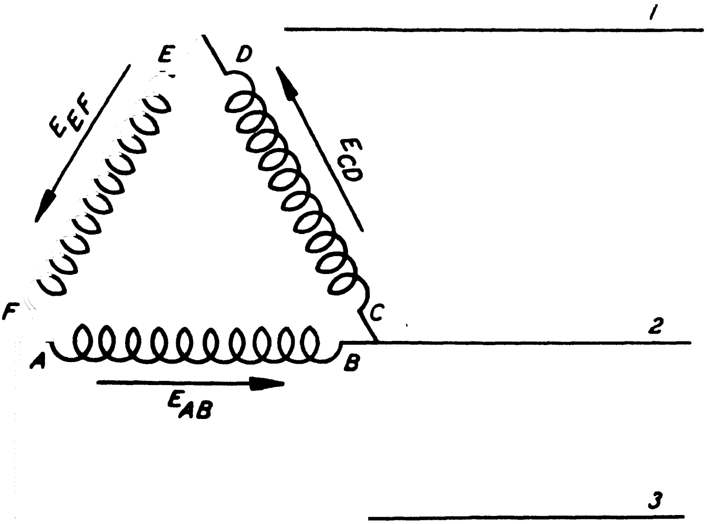


Fig. 151

If a fourth line wire (neutral) is used in the three-phase star circuit, the voltage from any line wire to this neutral line is, of course, equal to the phase voltage.

Now consider the voltage relations for the three-phase delta circuit (Fig. 151). In the first place, the connections are such that between any two line wires lies one phase and one phase only. Hence, the voltage between line wires is the voltage developed by only one phase, or in this case line voltage equals phase voltage. The vector diagram (Fig. 150) is merely a picture representing the three voltages at 120°. There is no vector addition or subtraction necessary since there is only one phase between a pair of line wires. In Fig.

152, we have added a curved arrow to show "phase rotation." In this picture, phase *AB* precedes phase *EF* by 120° E., and the latter in turn precedes phase *CD* by 120° *E*.

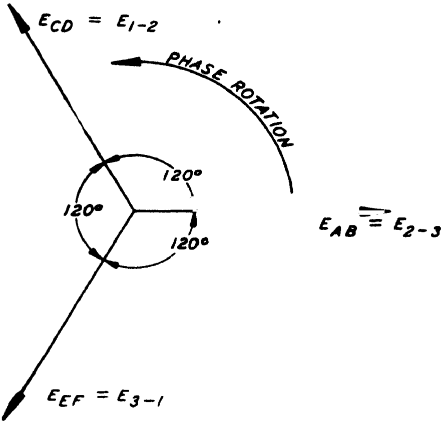


FIG. 152

To the student it may seem that the delta three-phase connection is possibly a short-circuiting of the three phases.

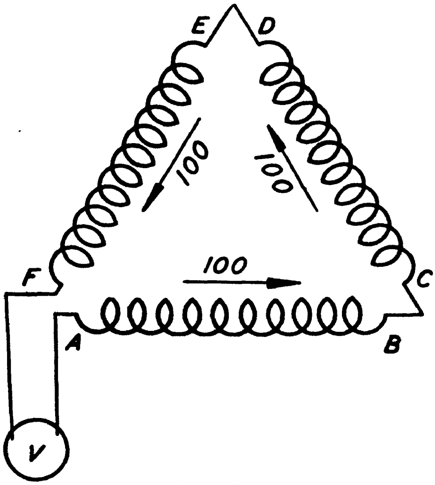


FIG. 153

This is, of course, not the case. Otherwise the delta connection could not be used. It is very easy to show that in reality the three phases together, taken as a series circuit just by themselves, result in zero voltage across the ends. Thus in Fig. 153, the three phases, *AB*, *CD*, *EF*, are joined in series, but the delta is not yet closed, as ends *A* and *F* remain unconnected. What would a voltmeter read if connected to the ends *A* and *F?* It would read the vector sum of the three-phase voltages, or $E_{AB} \oplus E_{CD} \oplus E_{EF}$.

Each phase voltage is 100 volts. If we add these three by the parallelogram method as in Fig. 154, we find that $E_{AB} \oplus$ E_{CD} at 120° gives a resultant of 100 volts exactly opposite in sense to E_{EF} the voltage of the third-phase *EF*. Hence two of the phases together in series produce a voltage exactly equal and opposite to the voltage of the third phase. Therefore the three together produce zero voltage. The voltmeter should then read zero when placed across points *AF*, and it is quite safe to join *A* and *F* to complete the delta connection.

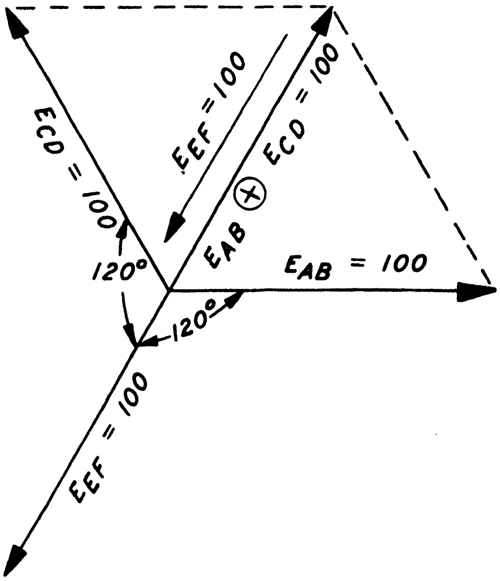


FIG. 154

The triangle method of adding vectors shows this result even more clearly. See Fig. 155.

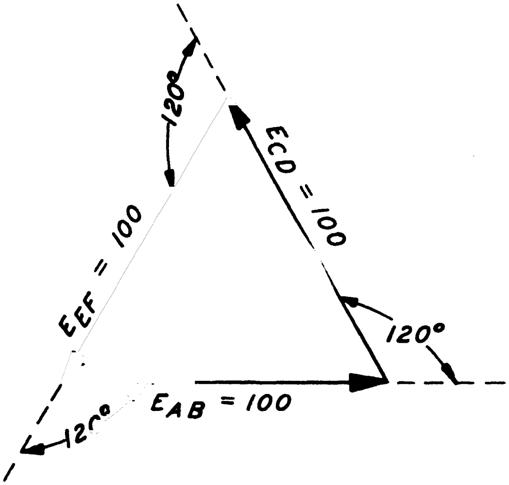


FIG. 155

37. THREE-PHASE CURRENT RELATIONS:

Next we raise the question concerning current conditions in a three-phase circuit. Let us start with the star circuit (Fig. 156). Observe first of all that each phase leads directly to one line wire. Thus phase *AB* leads to line wire 2. Any cur-

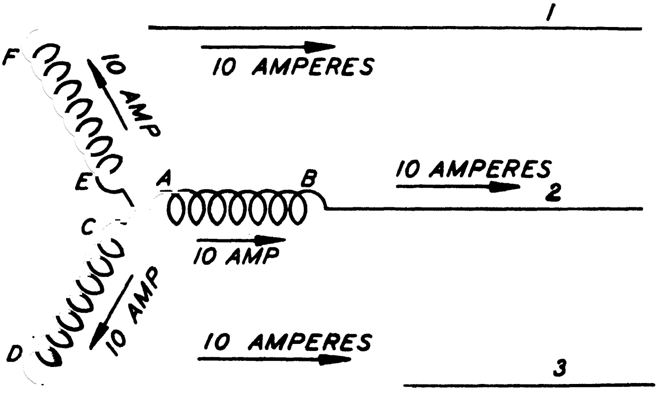


FIG. 156

rent passing through phase *AB* also passes through line wire 2. Hence the current in line wire 2 equals the current in phase *AB*, or $I_2 = I_{AB}$. Similarly $I_1 = I_{EF}$ and $I_3 = I_{CD}$. The line current in a star system equals the phase current.

In the delta three-phase system this is not true. The line current in a delta circuit equal $\sqrt{3}$ times the phase current. Let us see why this is so. Refer to Fig. 157. Observe that the arrows around the delta or mesh are as usual from start of phase to finish. It must be distinctly understood that these arrows are not intended to mean that at all instants currents flow in the sense shown by the arrow, because we know that an alternating current varies all the time and is alternately positive and negative. Neither do these arrows indicate that the currents at any one instant are simultaneously in the senses shown. These arrows mean simply that the positive sense of the voltage and of the current is as shown at 120° E. intervals. Thus phase *AB* reaches its positive maximum value, followed at 120° by the positive maximum of phase *CD*, and again followed at another 120° E. interval by the positive

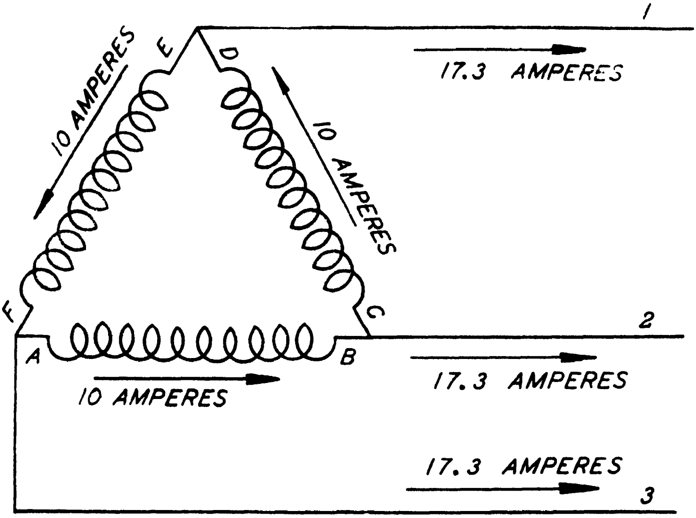


FIG. 157

maximum of phase *EF*. Similarly the arrows indicating current flow in the line wires 1, 2, 3, for both Figs. 156 and 157 (as also all similar three-phase pictures) mean that we have here chosen as our positive maximum in each line wire in turn (120° apart) the "out" direction. We could have chosen "in" if we wished. The result would not be different. But the student must not assume these arrows to mean that the current in these line wires is either "out" or "in" in all three at the same time. This is not the meaning of these arrows, but rather each arrow points the direction that we happen to choose as positive, one wire at a time (120° E. apart).

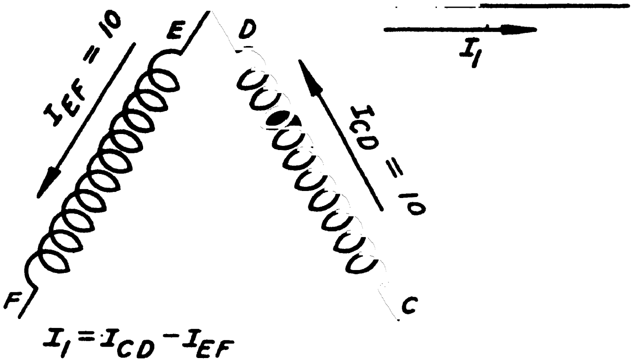


FIG. 158

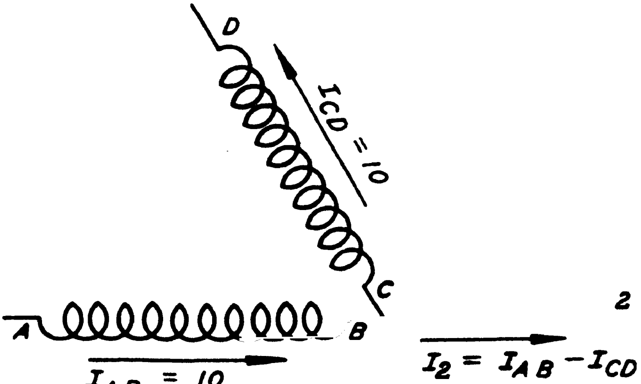


FIG. 159

With this in mind let us examine Fig. 157 more closely, one line at a time. Thus, Fig. 158 shows line 1, and the two phases which are connected to line 1. Note the arrows. Phase *CD* is feeding current toward line 1, while phase *EF* carries current away from line 1. Line 1 therefore gets the phase *CD* current minus what phase *EF* takes away. Or

$$I_1 = I_{CD} \ominus I_{EF}$$

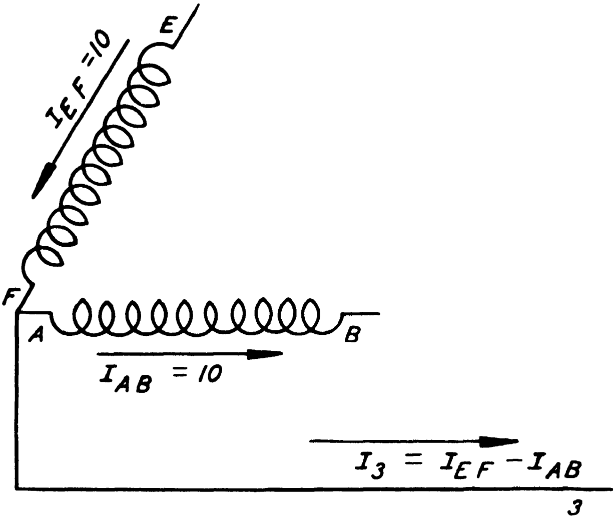


FIG. 160

Similarly from Figs. 159 and 160, we get

$$I_2 = I_{AB} \ominus I_{CD}$$

and

$$I_3 = I_{EF} \ominus I_{AB}.$$

In each case the line current equals the vector difference between two phase currents. Solving for I_1, I_2, I_3 by vectors, as in Figs. 161, 162, 163, we find that

$$I_1 = 17.3 \text{ amps.}$$
$$I_2 = 17.3 \text{ amps.}$$
$$I_3 = 17.3 \text{ amps.}$$
$$I_{\text{line}} = \sqrt{3} \times I_{\text{phase}}$$

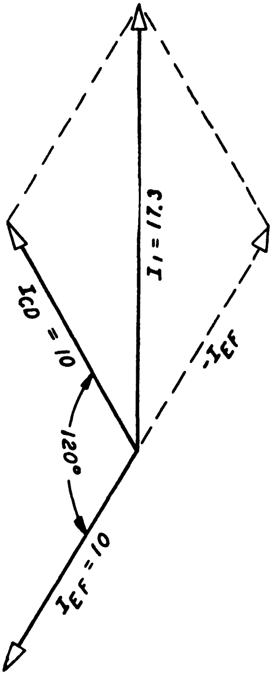


FIG. 161

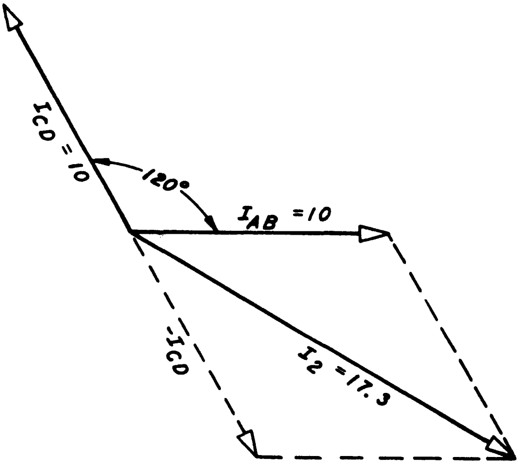


FIG. 162

These three may be considered in a single vector picture for the three phases. The result is shown in Fig. 164. Note that the line current is not only $\sqrt{3}$ times the phase current but that it is also 30° out of step with the phase current.

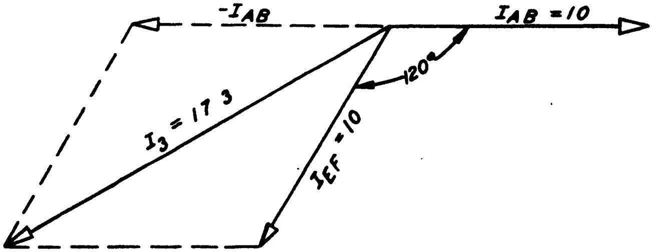


FIG. 163

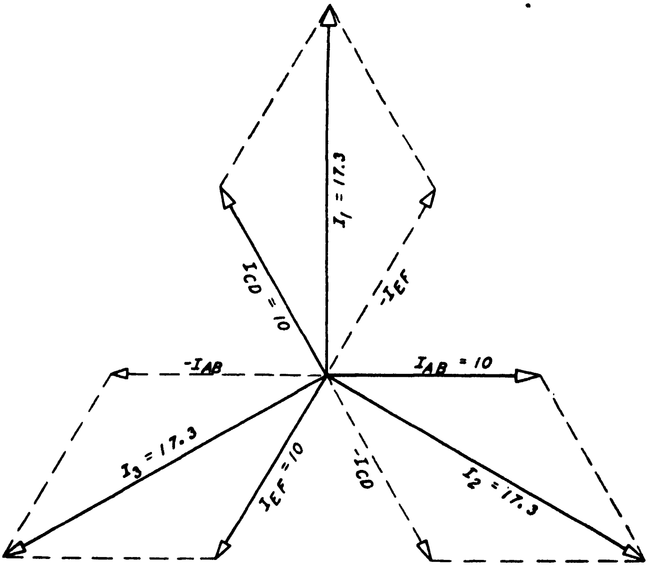


FIG. 164

38. UNBALANCED THREE-PHASE CIRCUITS:

In all of our discussions thus far we have assumed balanced conditions, that is, the currents in the phases all equal, hence line currents equal; also phase voltages equal, hence line voltages equal. This condition is not realized in actual practice. Individual local circuits may of course, be balanced, but in general circuits are unbalanced. Loads are variable, and consist of single-phase as well as three-phase equipment. Hence while it is very desirable to obtain balanced conditions, it is not always possible. In unbalanced three-phase circuits the relations discussed in the two preceding articles do not hold

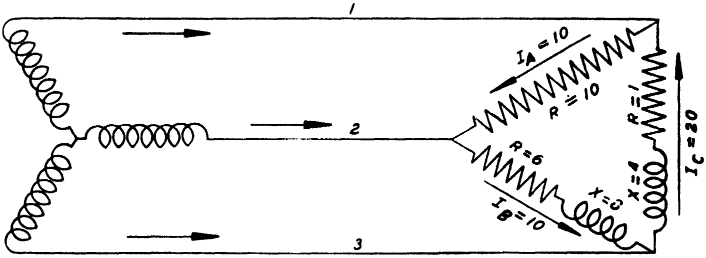


Fig. 165

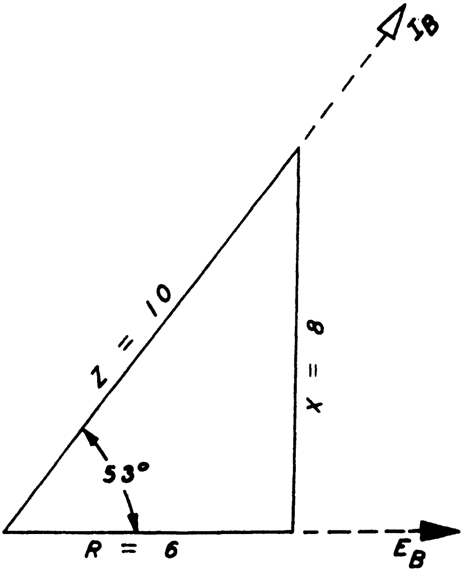


Fig. 166

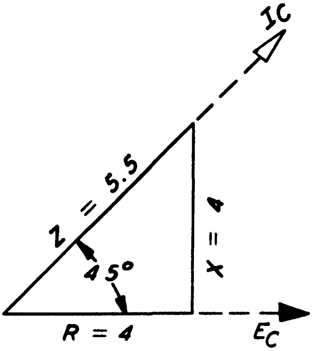


FIG. 167

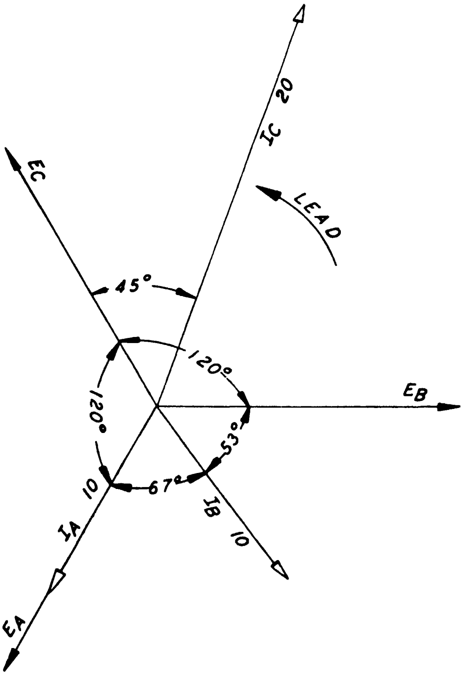


FIG. 168

strictly. They are true approximately, if a near-balance condition is attained, but are not even approximately true for badly unbalanced circuits. The solution for line voltage or line current is of course always possible by vectors, regardless of balance or unbalance. Thus, assume the circuit in Fig. 165. A three-phase star-connected generator supplies current to a delta-connected load as shown. Find the line currents, the phase currents for the alternator, and the currents in the individual phases of the load.

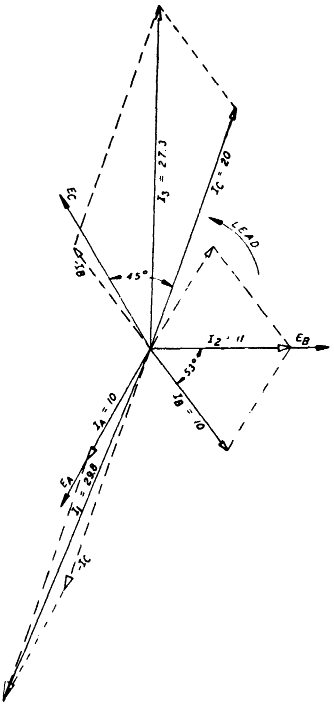


FIG. 169

First of all we should note the three-phase currents, I_A, I_B, I_C, are not in step with their respective line voltages because phase A contains resistance only, while phases B and C contain both resistance and inductive reactance. Hence in these two phases the current will lag behind the voltage across the phase. This angle of lag can, of course, be found by the impedance diagram for each phase. See Figs. 166, 167. We find from these that the phase angle in phase *B* is 53° and in phase *C* it is 63°. Now we are ready to draw our three-phase vector picture in order to solve for line currents I_1, I_2, I_3.

We begin by our voltage vectors. Assuming these as E_A, E_B, E_C, 120° E. apart as in Fig. 168, we locate the phase currents I_A, I_B, I_C at the proper phase angles with the respective voltages. The line current may now be found by combining the proper phase currents vectorially, as is done in Fig.

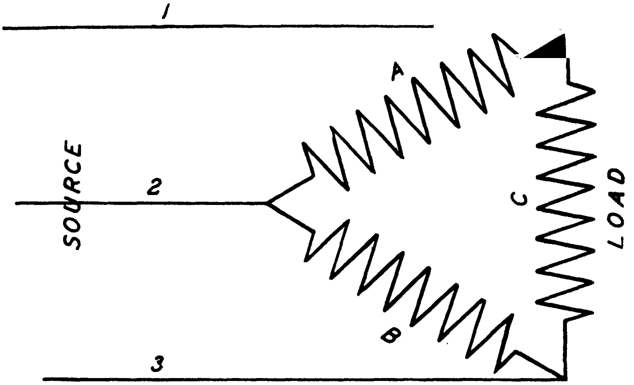


FIG. 170

169. Previously, however, we must choose the positive direction in the line wires and write our equations. Assuming positive current as "in" toward the load, as in Fig. 168, we have

$$I_1 = I_A \ominus I_C$$
$$I_2 = I_B \ominus I_A$$
$$I_3 = I_C \ominus I_B$$

Applying these as in Fig. 169 we find by the parallelogram addition of vectors,

$$I_1 = 29.0 \text{ amps.}$$
$$I_2 = 11.0 \text{ amps.}$$
$$I_3 = 27.3 \text{ amps.}$$

39. POWER IN THREE-PHASE DELTA OR STAR CIRCUITS:

We learned that the power in a single phase circuit is

$$P = EI \cos \Phi,$$

In a three-phase delta or star circuit the power should then be three times the power in any one phase. Now the power received by phase A of the delta circuit in Fig. 170 is

$$P_{\text{phase } A} = E_{\text{phase } A} \times \quad I_{\text{phase } A} \times \quad \cos \Phi_A.$$

But in the delta circuit

$$E_{\text{phase}} = E_{\text{line}}$$

and $$I_{\text{phase}} = \frac{I_{\text{line}}}{\sqrt{3}}$$

so that $$P_A = \frac{E \times I \times \cos \Phi_A.}{\sqrt{3}}$$

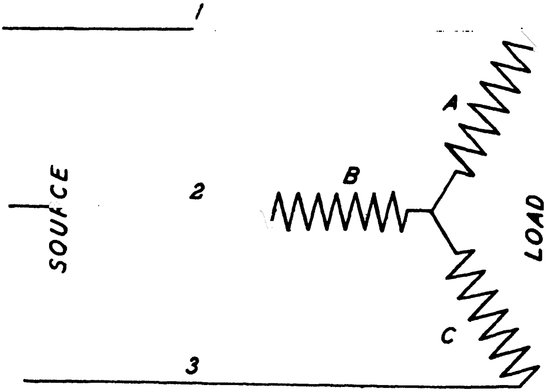


FIG. 171

And if the circuit is balanced, each phase receives the same load or power. Hence the three phases receive

$$P_{3 \text{ phase } \Delta} = \frac{3 \times E \times \ I \ \times \cos \Phi.}{\sqrt{3}}$$

the angle Φ being the same for all three phases. Simplified this becomes

$$P = \frac{3\ EI \cos \Phi.}{\sqrt{3}}$$

or $$P = \sqrt{3}\ EI\ \cos\ \Phi.$$

in which, E is line voltage, I is line current. Similarly for a three-phase star circuit if balanced, the power is three times the power received by one phase. See Fig. 171.

$$P_{\text{phase } A} = E_{\text{phase } A} \times I_{\text{phase } A} \times \cos \Phi.$$

but here, $$E_{\text{ phase } A} = \frac{E_{\text{line}}}{\sqrt{3}}$$

$$I_{\text{ phase } A} = I_{\text{line}}$$

so that $$P_{\text{ phase } A} = \frac{E_{\text{line}} \times I_{\text{line}} \times \cos \Phi}{\sqrt{3}}$$

and for the three-phase

$$P = \frac{3 \times E_{\text{line}} \times I_{\text{line}} \times \cos \Phi.}{\sqrt{3}}$$

or $$P = \frac{3\ EI\ \cos\ \Phi.}{\sqrt{3}}$$

$$= \sqrt{3}\ EI\ \cos\ \Phi$$

in which E is again line voltage and I is line current. Three-phase power, whether in star or delta circuits, is therefore the same. The formula

$$P = \sqrt{3}\, EI \cos \Phi$$

is true for balanced circuits only. It is approximately true for slight unbalances, but becomes erroneous for very serious unbalanced conditions.

Power in three-phase circuits is usually measured by two wattmeters or by a polyphase wattmeter, although in a balanced circuit one wattmeter could be used. The connections for the various methods of measurement are given in the chapter on meters.

When the two wattmeter method is used, the total power measured is the algebraic sum of the individual readings. This suggests that the readings are not always both positive. In circuits with power factors below 50%, one wattmeter reads positive, the other negative. In order to know for sure that both read positive, or that one reads negative, it is very necessary that the two instruments be connected to the circuit "symmetrically." See the next chapter, "METERS."

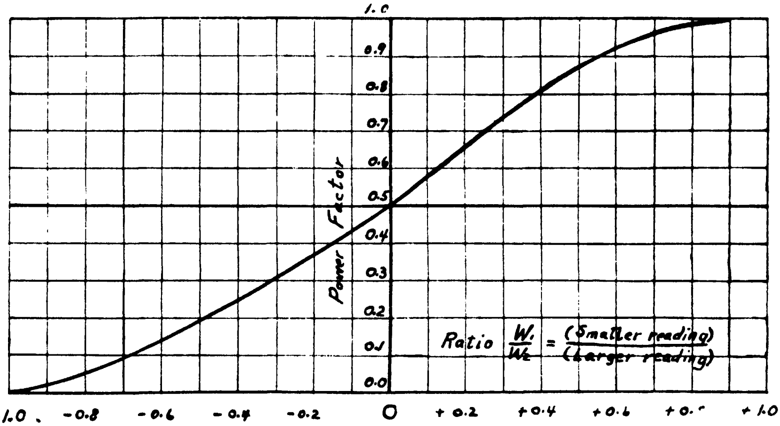


FIG. 172

When the power factor is unity, cos $\Phi = 1.00$ or when Φ is 0°, the reading of both wattmeters is the same. When the power factor is 50% or 0.5, one wattmeter reads zero. This occurs when the angle Φ is 60°, either leading or lagging. The ratio of the two readings W_1 to W_2 may be used to find the power factor of the circuit, in connection with a graph shown in Fig. 172.

40. OPEN DELTA THREE-PHASE:

It is possible to maintain a three-phase delta service even though one of the three phases is disconnected, such as when one phase is damaged. Thus (Fig. 173), phases *AB* and *CD* are in use, *EF* is disconnected. The voltage between each pair of line wires is 100, since phase *AB* puts 100 volts across lines 2-3, phase *CD* puts 100 volts across lines 1-2, and lines 3-1 are across *AB* and *CD* in series. But these two together at 120° produce 100 volts. Hence lines 3-1 also get a voltage of 100 volts. See Fig. 174. The capacity of the three-phase unit is reduced to 58% in this case. Transformers are sometimes joined in this fashion. The connection is known as the "open delta" or *Vee-connection.*

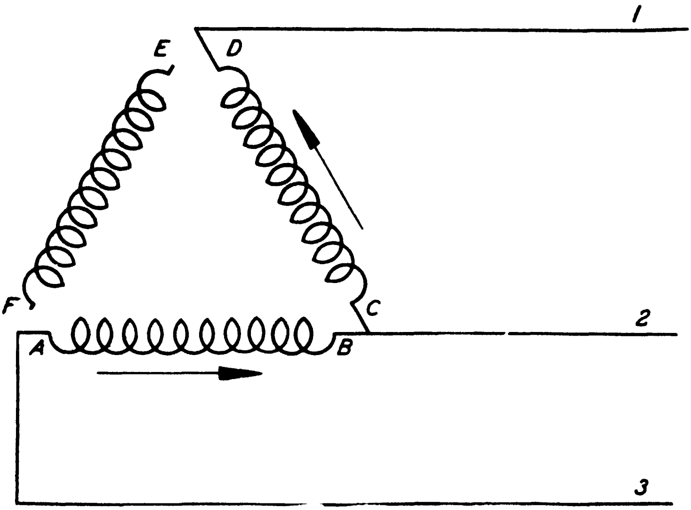


FIG. 173

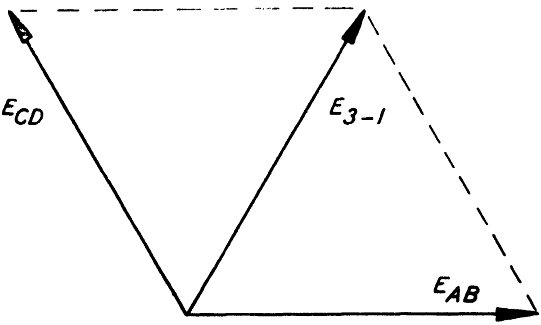
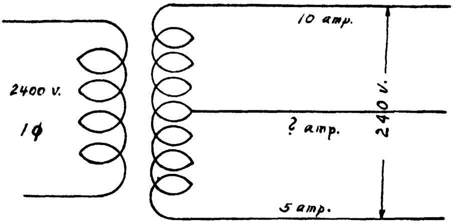


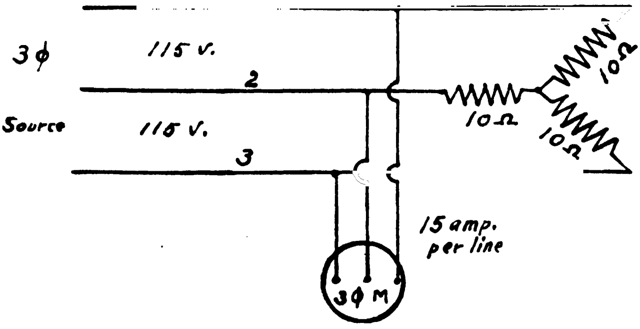
FIG. 174

PROBLEMS—CHAPTER IV

1. The accompanying figure shows the wiring diagram for the distribution transformer that brings power to your home. Suppose one of the outside wires leading into your house carries 10 amperes (lighting current) and the other carries 5 amperes. What current flows in the middle line wire?

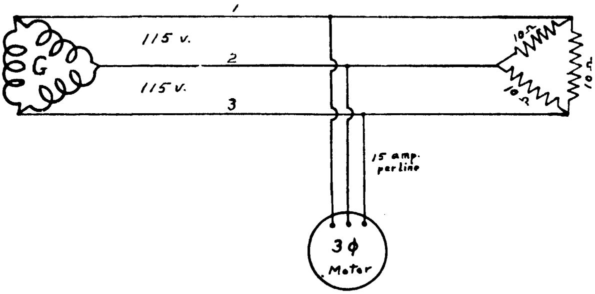


2. Draw a vector picture which would show the 230 volts, the 115 volts across the upper "leg" (half) of the three-wire, and the 10 amperes in this leg.
3. If the 5 amperes in problem 1 represented in part lighting current and in part current to the washing machine motor, would the line current be leading, lagging, or in phase? Show this by vector picture.



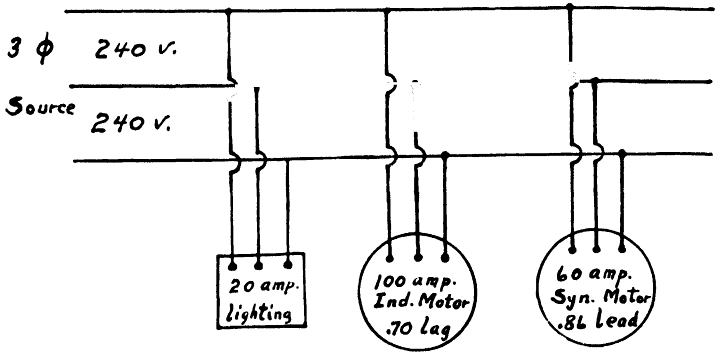
4. A two-phase generator develops 110 volts per phase. The current from phase *A* is 10 amperes, used for lighting and for a heater; the current from phase *B*, also 10 amperes, is used for a motor at a power factor of 80%. Draw the vector picture that fits this data, assuming this to be a four-wire circuit.

5. If the circuit above were three-wire, what would be the current in each outside line wire? In the middle line wire? Solve for the latter by vectors.
6. In problem 5, what is the voltage between the middle line and either outside wire? Between the two outside lines?
7. Suppose that the currents in both phases of problem 4 are "in phase" currents, and that the circuit is three-wire. Draw the vector picture and solve for current in the middle line.
8. In the accompanying figure, a three-phase alternator furnishes current to a combination of single-phase and three-phase loads. Find the voltage across each of the three resistances R_1, R_2, R_3. (Assume the line drop to be negligible.)
9. How much current flows through each of the resistances R_1, R_2, R_3?
10. Each line wire also supplies 15 amperes to the three-phase motor. What is the total line current, assuming the power factor of the motor to be 86.6%?
11. What is the power factor of this three-phase circuit? Also the phase angle of lead or lag?
12. What is the total current in each of the three alternator phases *A, B, C,* assuming the phases connected in star? In delta?



13. Assume the three-phase delta arrangement shown in the accompanying figure. R_1, R_2, and R_3 each equal 10 ohms. Each line wire 1, 2, 3, feeds 15 amperes to the motor. What is the voltage across each resistance R_1, R_2, R_3 if each generator phase develops 115 volts?
14. What current flows in each of the resistances R_1, R_2, R_3?
15. What current does each line wire 1, 2, 3, feed to the resistances R_1, R_2, R_3 arranged as they are in delta?

16. What is the total current in each line wire, assuming the motor power factor to be 86.6% lagging?
17. What is the power factor of the whole circuit? Also the phase angle of this circuit?



18. The circuit shown in the accompanying diagram is a balanced three-phase. Find the current in the line wires 1, 2, 3, assuming that the synchronous motor (leading current) is disconnected.
19. If the synchronous motor is connected to the lines along with the other apparatus, what is the current in line wires 1, 2, 3?
20. Assume that only the two motors are connected to the line. What current flows in each line wire 1, 2, 3?
21. What is the power factor of the circuit as it exists in problem 20? What has been the effect of adding the synchonous motor with leading current, to the induction motor with lagging current?
22. What power is delivered by each phase of the two-phase generator in problem 4? What is the total power delivered?
23. What is the power delivered to the three-phase motor in problem 8? To the three resistances? To both together?
24. Find the total power delivered by the delta generator in problem 13.
25. Find the total power delivered by the star-connected alternator in problem 18, to the two three-phase motors, assuming these to be the only loads on the alternator.

CHAPTER V

ALTERNATING CURRENT METERS

41. CLASSIFICATION OF METERS:

Control of the electric current and of electrical appliances is not only desirable—it is necessary. Scientific and economic control depends upon accurate measurement. Measuring instruments differ in construction and use, according to the purposes for which they are intended, according to the principle upon which their action is based, and according as they are intended for use on direct current or alternating current circuits. Thus, the hot-wire ammeter depends for its action upon the heating effect of the electric current. On the other hand, an electric current also has a magnetic effect. Direct current ammeters and voltmeters are commonly based upon the attractive force between a permanent magnet and a movable coil of wire that carries current. Other meters depend basically upon the force of attraction or repulsion between two coils, both of which carry current. These latter are said to be of the electrodynamometer type.

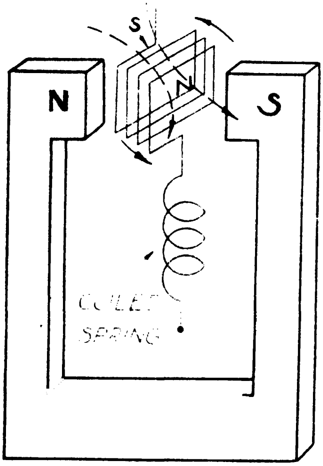


FIG. 175

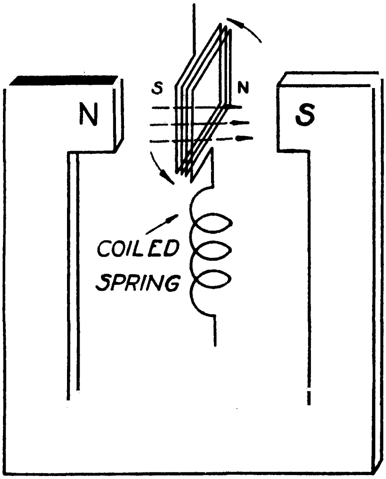


FIG. 176

42. ESSENTIAL PARTS OF METERS:

The electric current or currents passing through any meter gives rise to a force which causes a movable part to move. This force is ordinarily the result of magnetic interaction. Suppose a coil of wire to be suspended between the two ends of a magnet shaped as in Fig. 175. When current flows through the coil, as shown in the illustration, the coil becomes magnetized, the front face being of north polarity and the rear face, south. Obviously, if the suspended coil were free to turn it would assume the position shown in Fig. 176.

Similar results are obtained by substituting for the permanent magnet in Figs. 175, 176 an electromagnet. Thus, Fig. 177 shows a fixed coil in two parts between which is suspended a movable coil. When both circuits are energized, mutual attraction between the coils will cause rotation of the movable coil. In Fig. 175 there is apparently no reason why the suspended coil should not always come to the position shown in Fig. 176, regardless of the size of the current. If the suspended coil be made to turn against the resisting force of a spring, then the number of degrees that the suspended coil turns through depends upon the size of the current flowing. The spring may be helical or spiral in shape. Usually a

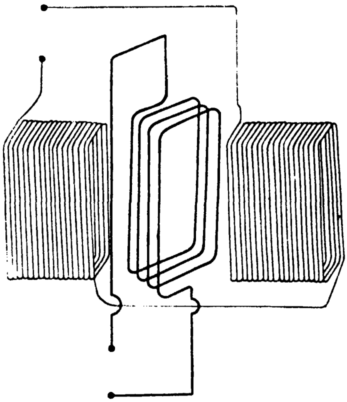


FIG. 177

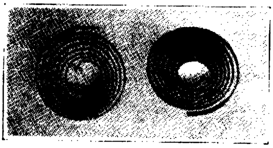


FIG. 178

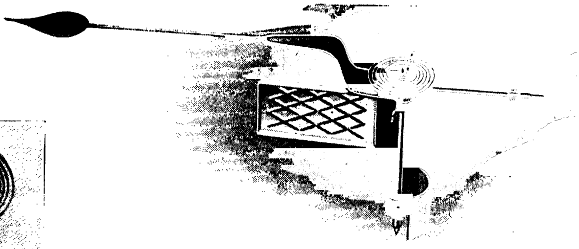


FIG. 179

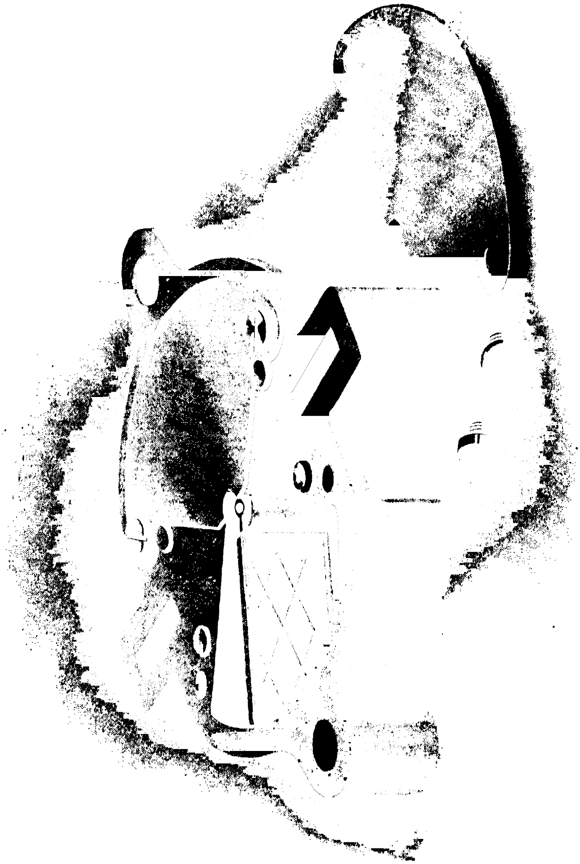


FIG. 180

very slender phosphor bronze ribbon or wire is used in meters. See Figs. 178, 179.

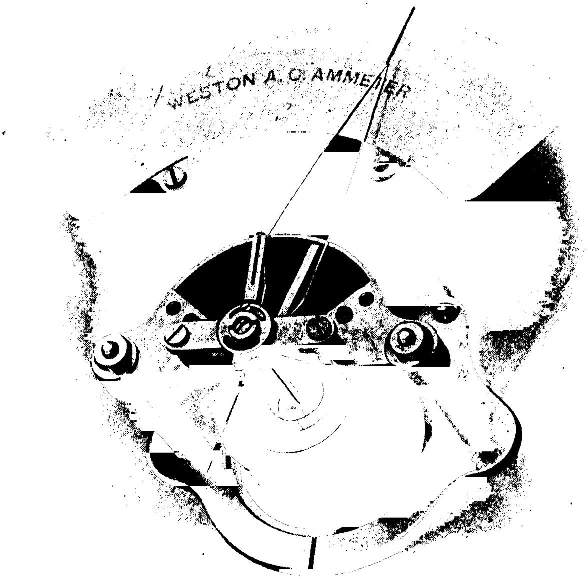


FIG. 181

Observe also the rectangular vane which is part of the moving element shown in Fig. 179. This vane moves in an air

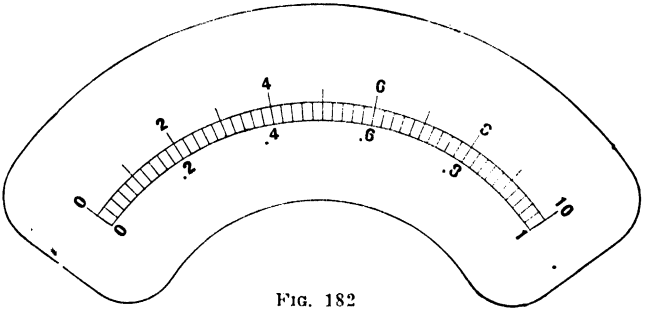


FIG. 182

chamber so arranged that the resistance of the air affords a means of damping the motion of the moving element. This does not, of course, take the place of the coiled spring but makes the motion smooth. See Figs. 180, 181. This spring so controls the rotation of the moving element that the amount of rotation is proportional to the current or voltage

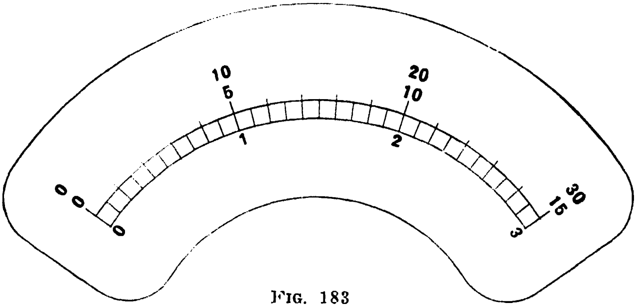


FIG. 183

and hence is a measure of the current or voltage which caused the rotation.

Another essential part of a meter is the scale. Some meters have a single scale, others have multiple scales. See Figs. 182, 183. Recording or graphic meters have charts or cross-

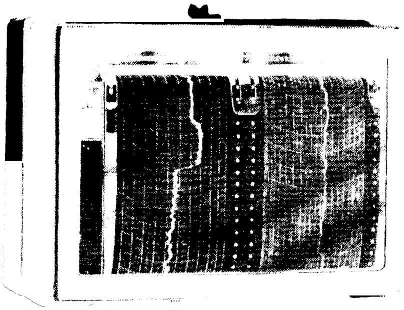


FIG. 184

section sheets which must be renewed at definite time intervals, as for example, every twenty-four hours. Such a chart is shown in Fig. 184. The pointer or needle of the indicating meter and the recording device (Fig. 185) for the graphic meter are also essential parts.

A further feature worth considering is the method of suspending the movable coil. In some instruments (laboratory galvanometers), the coil hangs by a slender phosphor bronze or silken thread. Usually, however, the movable coil is mechanically pivoted between two jewelled bearings. The sapphire and more recently the diamond have been used for this purpose. Meters are therefore sensitive, and the construction is delicate like that of a watch. It is necessary to handle meters carefully if the accuracy of an instrument is to be maintained. There are, of course, meters more rugged in type, but ruggedness is obtained at the expense of accuracy.

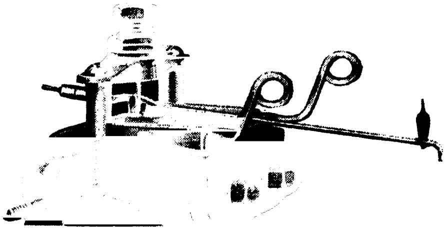


FIG. 185

Finally the working part of a meter must be suitably encased to afford proper protection, and terminals must be made available to enable easy connection to a circuit. It may be suggested here that metal terminals usually indicate current measurement (ammeters), and insulated terminals indicate potential measurement (voltmeters). See Figs. 186, 187.

FIG. 186

FIG. 187

Alternating current meter terminals have no polarity marking. One terminal is marked ±, the other is marked to indicate scale range.

43. ELECTRODYNAMOMETER TYPE METERS:

It was previously suggested that in this type of meter there is no permanent magnet but instead there is a two-part stationary "field coil." The movable coil is mounted between the two parts of the field coil. See Fig. 188.

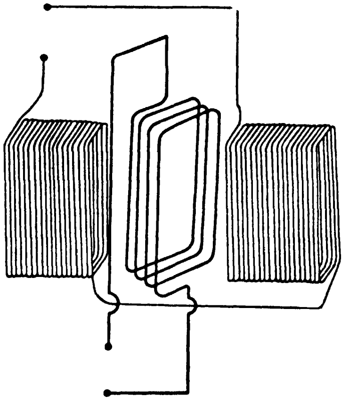


FIG. 188

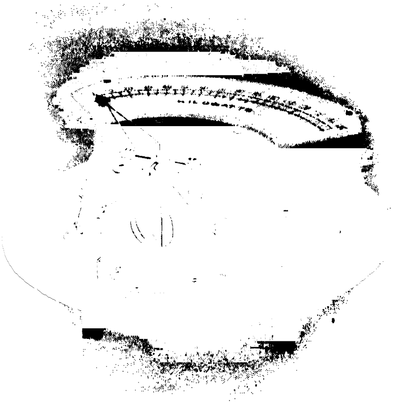


FIG. 189

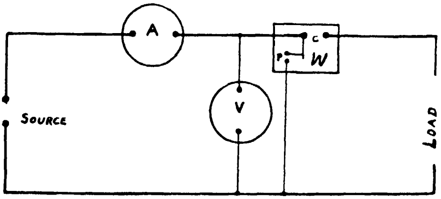


FIG. 190

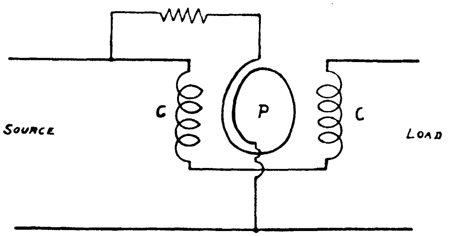


FIG. 191

Wattmeters are commonly built in this way. The fixed coil is the current coil or ammeter part of the instrument, while the moving coil is the potential or voltmeter part of the instrument. Fig. 189 shows the two parts of the current or field coil and mounted between these two parts is the movable coil. A high resistance is joined in series with the latter just as in the case of a voltmeter. The connections for a wattmeter are shown in Figs. 190, 191.

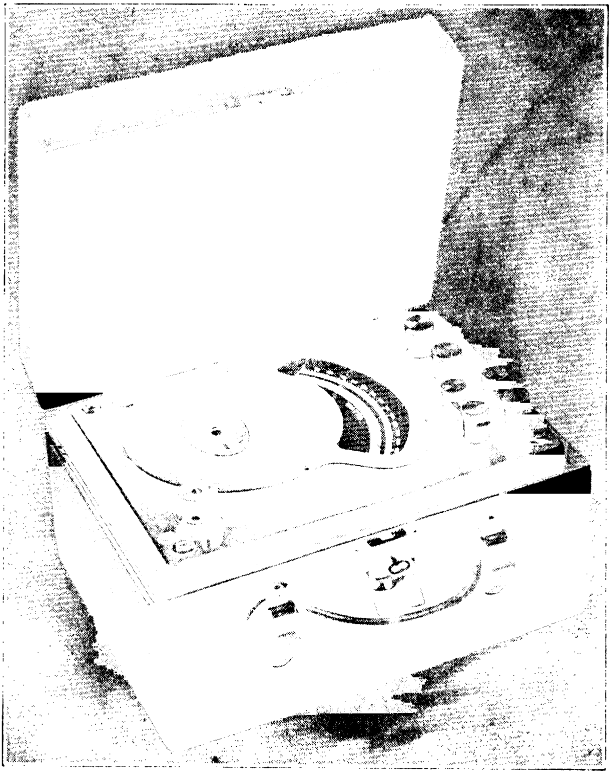


FIG. 192

Provision is often made to allow the two parts of the field coil to be connected in series or in parallel, thus permitting a double current capacity if desired. The Weston Model 310 is of this type. See Figs. 192, 193. In 3-wire systems, whether two-phase or three-phase, two single-phase watt-

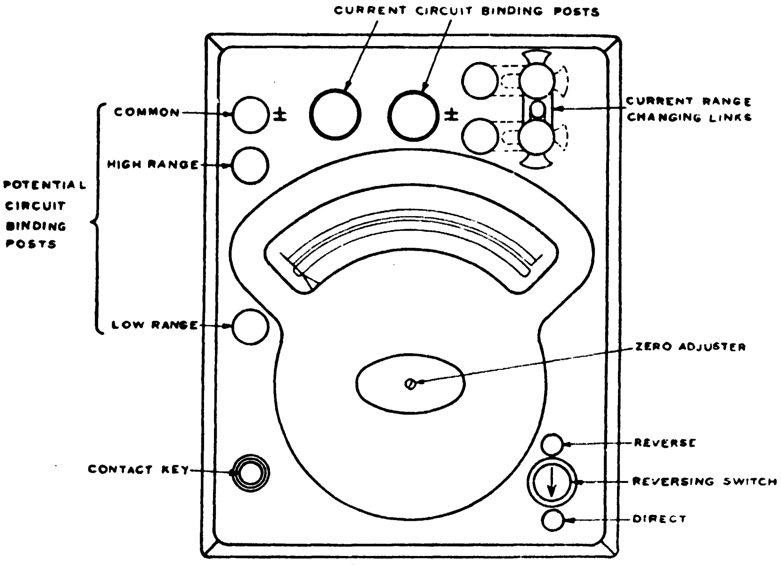

CURRENT CIRCUIT BINDING POSTS
COMMON
±
±
HIGH RANGE
POTENTIAL CIRCUIT BINDING POSTS
LOW RANGE
CURRENT RANGE CHANGING LINKS
ZERO ADJUSTER
CONTACT KEY
REVERSE
REVERSING SWITCH
DIRECT

FIG. 193

meters can be used to measure the power. The total power is the sum of the two readings. Connections are as in Fig. 194.

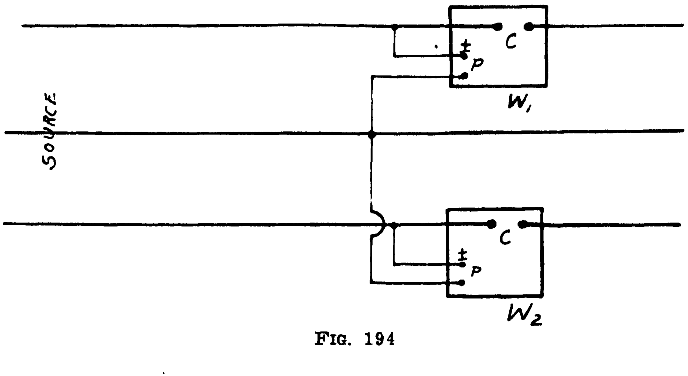


FIG. 194

Or instead of the two single phase wattmeters one instrument which comprises within itself the essential parts of two single-

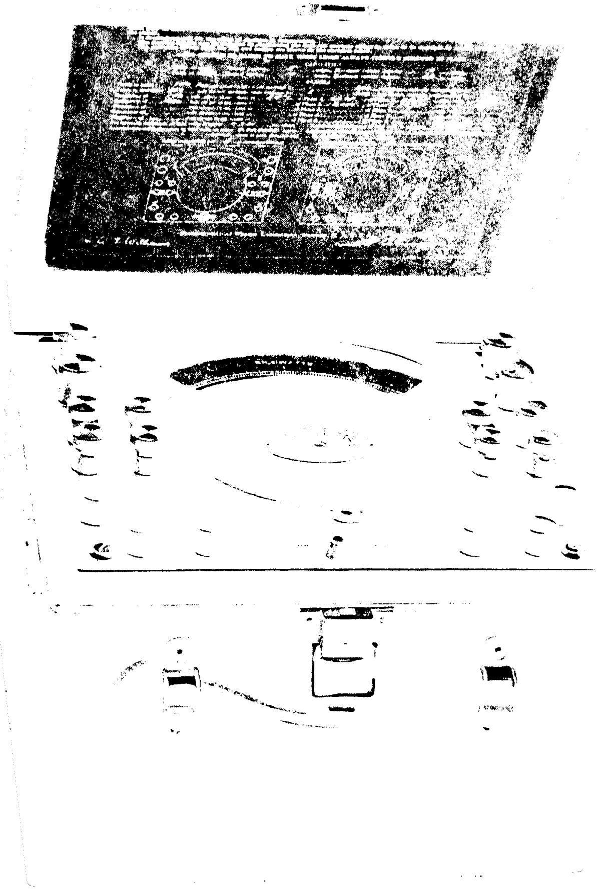


Fig. 195

phase wattmeters can be used to measure power in three wire circuits. Such an instrument is called a polyphase watt-

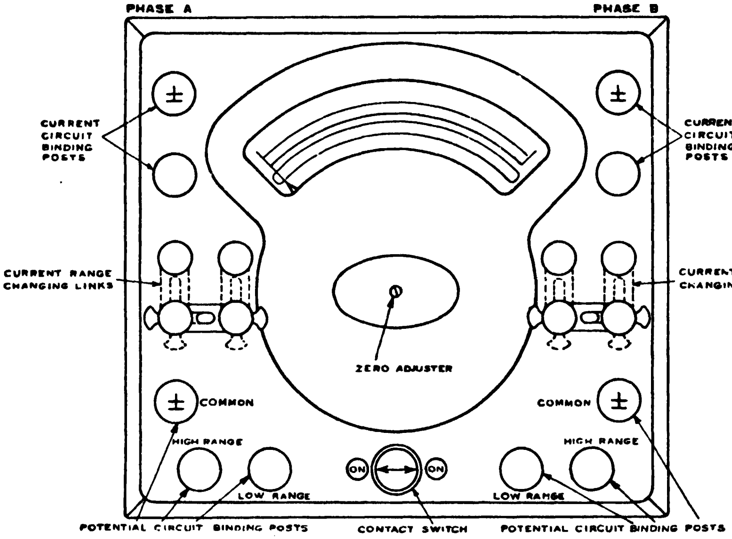

PHASE A
PHASE B
CURRENT CIRCUIT BINDING POSTS
CURRENT CIRCUIT BINDING POSTS
±
±
CURRENT RANGE CHANGING LINKS
CURRENT RANGE CHANGING LINKS
ZERO ADJUSTER
COMMON
COMMON
HIGH RANGE
HIGH RANGE
LOW RANGE
LOW RANGE
ON
ON
POTENTIAL CIRCUIT BINDING POSTS
CONTACT SWITCH
POTENTIAL CIRCUIT BINDING POSTS

FIG. 196

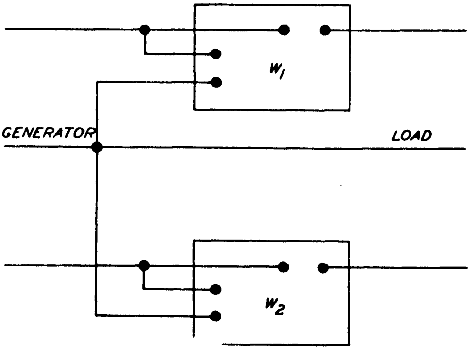


FIG. 197

meter. The Weston Model 329 is shown in Figs. 195, 196. The connections are as shown in Figs. 197, 198, 199.

In the two-wattmeter method of measuring power, connections must be made "symmetrically," that is, similar ter-

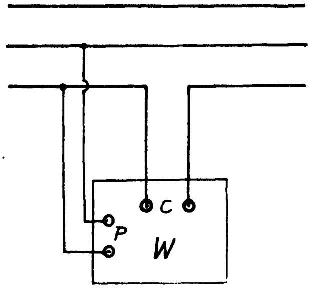
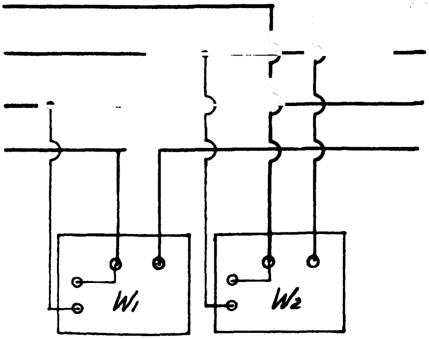


FIG. 198



2-Phase 4-Wire

FIG. 199

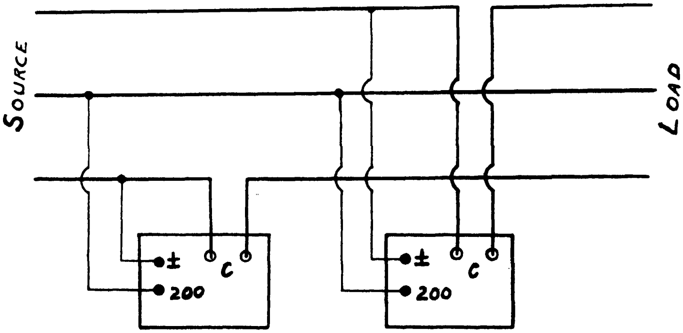


FIG. 200

minals on the two wattmeters must be connected to corresponding points in the circuit. Thus in Fig. 200, note that the potential terminal marked ± on both wattmeters is connected to the line which feeds through the current coil, while the other potential terminal on both meters is connected to

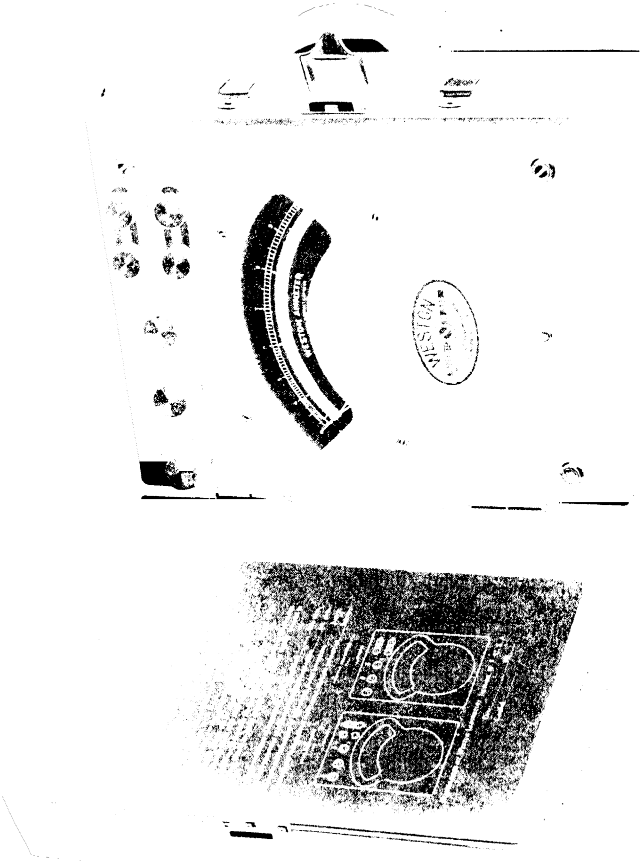


Fig. 201

the middle line. Similarly, the left-hand current terminal on both wattmeters is connected to the source side of the line, while the right-hand current terminal is connected to the load side of the line. With the symmetrical connection both watt-meters should read positive, unless the power factor of the circuit is less than 50%, in which case one meter reads negative.

Fig. 202

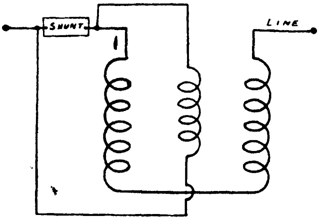


Fig. 203

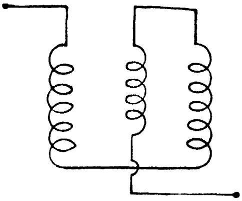


Fig. 204

Voltmeters and ammeters of the dynamometer type are made by some manufacturers, and such instruments may be used on either A.C. or D.C. circuits. Thus the Weston Electrical Instrument Company has developed a Model 370

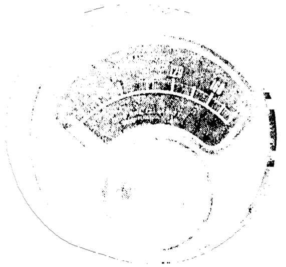


Fig. 205

ammeter and a Model 341 voltmeter. See Figs. 201, 202. The connections within the ammeter and voltmeter cases are shown respectively in Figs. 203, 204. The finer wire for the

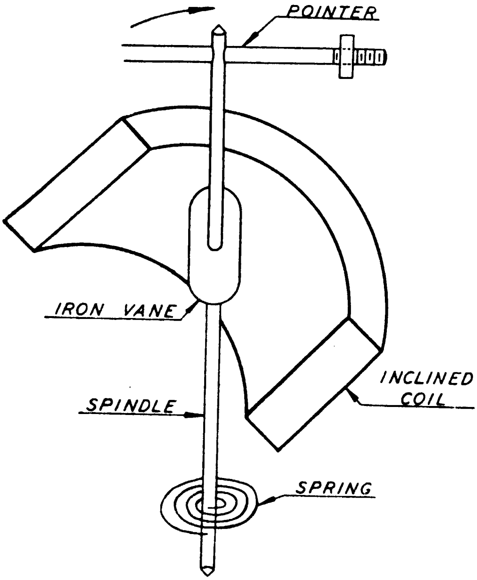


Fig. 206

voltmeter field coils is intended to supply the necessary high resistance to limit the current when the line voltage is connected to the voltmeter terminals.

Other electrodynamometer type instruments manufactured are the synchroscope, the frequency meter, and the power factor meter. These will be discussed in subsequent sections.

44. ELECTROMAGNET TYPE VOLTMETERS AND AMMETERS:

Fig. 205 shows a type R-6 switchboard ammeter of the inclined coil moving vane type, made by the General Electric Company. The current to be measured passes through the fixed inclined coil. A thin piece of iron fastened to the spindle, also at an angle, is free to move with the spindle, against the resisting force of a spring as shown in Fig. 206. When current flows through the fixed coil the magnetic effect which it produces influences the iron vane. The latter tends to assume a position in line with the magnetic field through the coil as shown in Fig. 207. In doing so it rotates the shaft and the pointer.

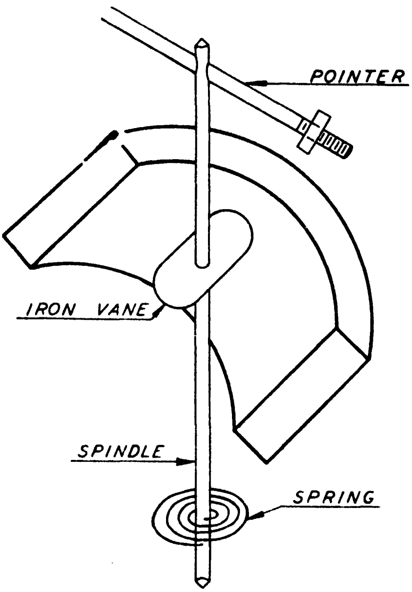


FIG. 207

A very simple form of instrument based on the electromagnetic principle is the "plunger" type of ammeter and voltmeter. In the plunger type of instrument the pointer is attached to a piece of soft iron or to a vane made of soft iron. In either case the soft iron is movable. The current to be measured flows through a stationary coil or solenoid and the soft iron is pulled into the coil due to magnetic interaction between solenoid and iron. Fig. 208 illustrates the general construction of a plunger type of instrument. The voltmeter differs from the ammeter in that a high resistance is connected in series with the solenoid.

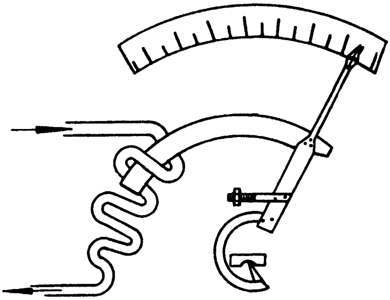


Fig. 208

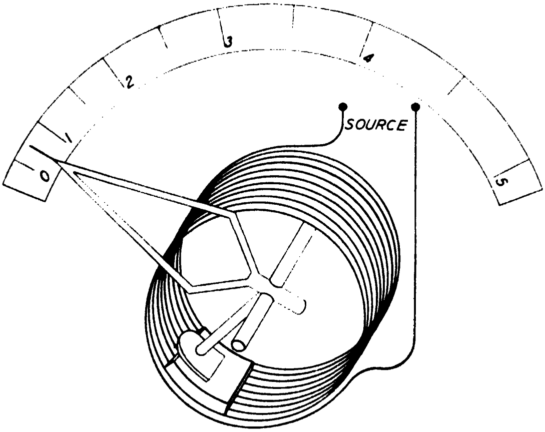


Fig. 209

The Weston Model 155 is an ingenious development of the basic principle of repulsion between like magnetic poles.

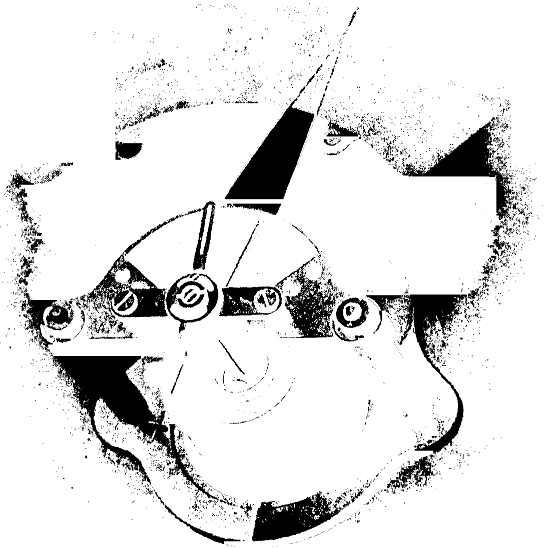


FIG. 210

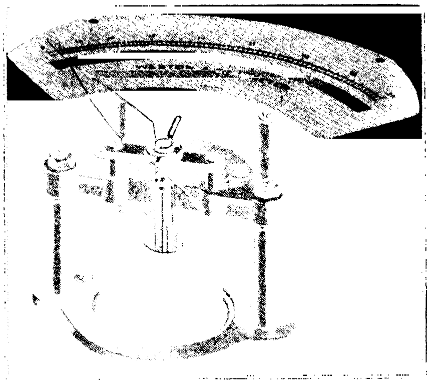


FIG. 211

Two pieces of iron of somewhat different shapes are arranged inside a coil as shown in Fig. 209. When current flows through the coil, which is fixed, the magnetic field produced inside of the coil magnetizes both pieces of iron in the same way. The one being fixed, the other movable, it follows that the repulsion between the two pieces of iron (since like poles are adjacent) causes the movable piece to rotate and with it the shaft and the pointer rotate also. Observe the arrangement of parts in Fig. 210 and in Fig. 211. Note that the coil consists of a very few turns of heavy wire or light copper bar. On the other hand, Fig. 212 shows a voltmeter similar in construction but having a coil of many turns of fine wire.

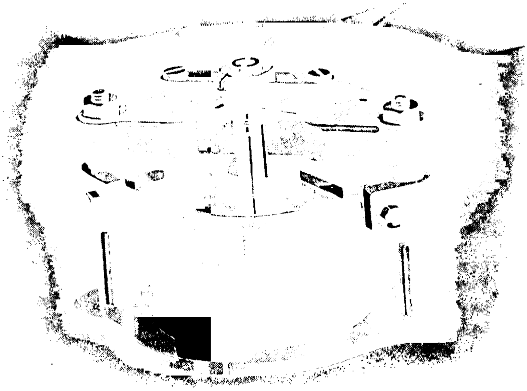


FIG. 212

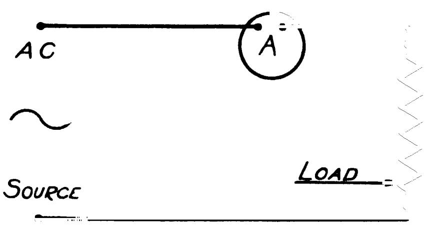


FIG. 213

The connections of A.C. ammeters and voltmeters are like the connections of the D.C. instruments. They are shown in Figs. 213, 214.

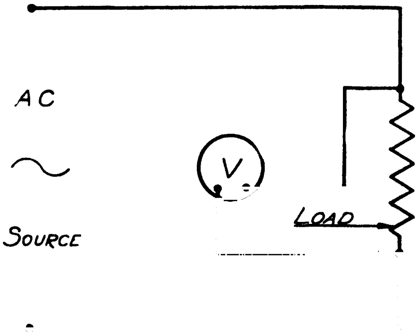


Fig. 214

For very large current measurement or for high voltage measurement such as is necessary in central stations, ammeters and voltmeters, and for that matter other instruments

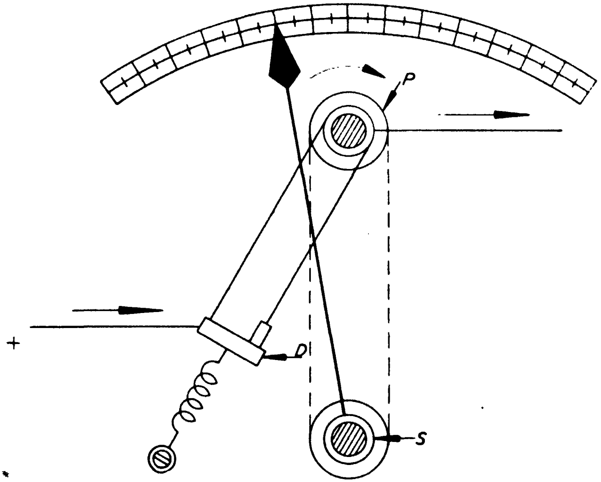


Fig. 215

as well, are not directly connected to the circuit, but are connected through instrument transformers. This is done to protect the operator. Instrument transformers extend the ranges of the ordinary ammeters and voltmeters. See section 49.

45. HOT-WIRE INSTRUMENTS:

Hot-wire meters are based upon the heating effect of the electric current. Fig. 215 illustrates the construction of a Roller-Smith hot-wire meter. The wire that carries the current (made of a special alloy) passes around a pulley *P* and its two ends are fastened to a metal disk *D*, one end being insulated from the disk. A spring holds the wire taut. The current passes through only one side of the wire looping the pulley, hence only this side elongates due to the heating effect.

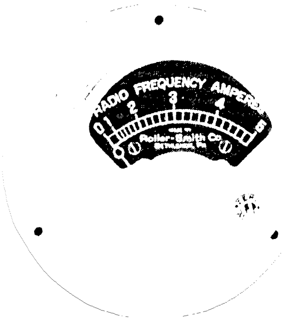


FIG. 216

The shaft *S* transmits the pulley motion to the pointer *P* to give a scale reading. Hot-wire instruments are not designed for accurate measurements, but they are still used for certain classes of work. Thus the Roller-Smith ammeter shown in Fig. 216 is used for current measurement in radio frequency circuits.

46. THERMAL INSTRUMENTS:

Thermal instruments are not to be confused with hot-wire instruments, although the heating effect of the current is again basic. Another principle is involved as well, however. It is the thermocouple principle, which briefly is as follows. When two unlike metals are in contact and heat is applied at the place of contact, a small electromotive force is produced.

In Fig. 217, a thermocouple consisting of a bismuth-antimony junction is mounted above a heater wire. The current through the instrument is made to pass through the heater, thus causing it to heat the thermocouple. The small electromotive force developed in this way, sends a current through the single loop coil *C*. The latter is suspended by a fine quartz thread between the two poles of a permanent magnet. Regardless as to whether the current through the heater is D.C. or A.C., the coil current is always in the same direction and hence it rotates only one way.

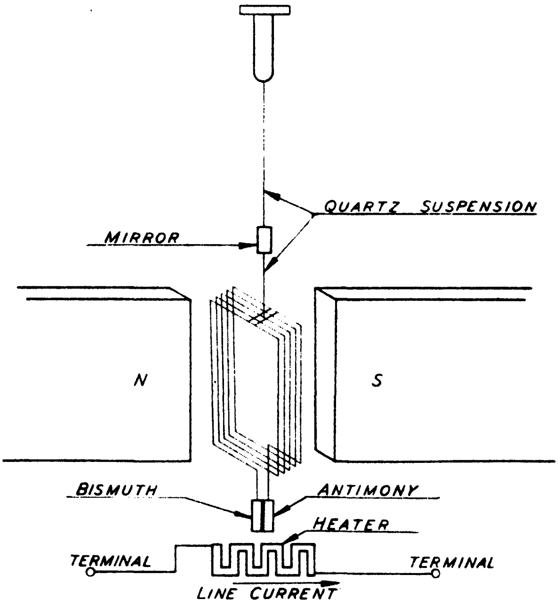


FIG. 217

Thermal instruments are especially useful for radio frequency current measurement, as for example, antennae current measurements. The Weston Model shown in Fig. 218 shows a switchboard thermoammeter of this kind.

Thermal instruments are obviously limited in use to the measurement of relatively small currents. Research laboratories and radio stations find thermal instruments well adapted to their needs.

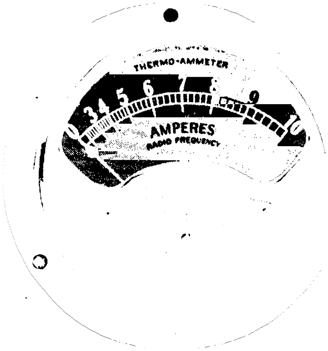


FIG. 218

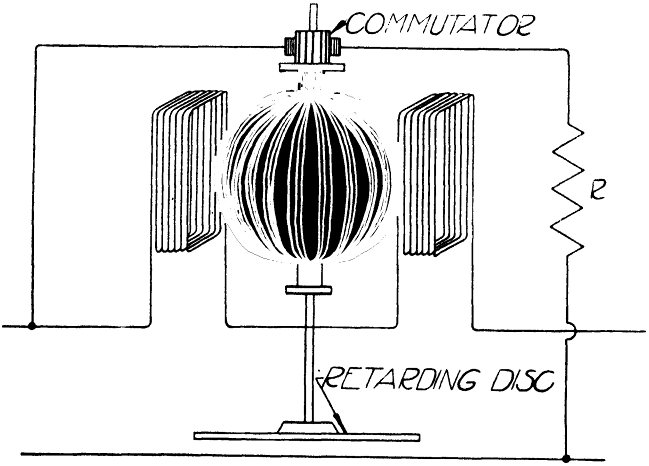


FIG. 219

47. THE WATT-HOUR METER:

Power is the rate at which energy is being supplied or consumed, and it may therefore vary from instant to instant. If we multiply the average rate at which energy is supplied by the length of time it is supplied, we obtain the total energy furnished. Hence, the equation:

$$W = P \times t$$

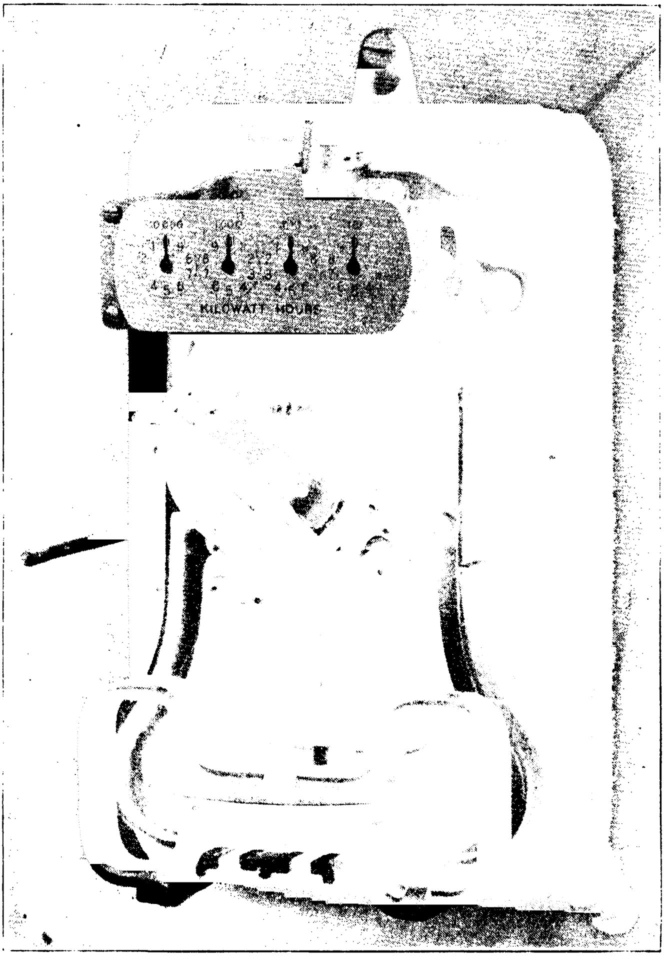


FIG. 220

One thousand watt-hours equals one kilowatt-hour. A meter that records the energy delivered by an electric current in terms of watt-hours is called a watt-hour meter. It is by means of the watt-hour meter that power and light companies measure the energy supplied to customers and render bills.

Watt-hour meters are electrodynamometer instruments or induction type instruments according to the principle upon which their construction is based. The essential features of the electrodynamometer type are shown in Fig. 219.

While this type of meter may be used on both D.C. and A.C. circuits, it is more commonly used on the former. The stationary coils (current) may carry either all or a part of the current and may be joined either in series or in parallel. The movable coil (potential) is mounted to permit rotation like a motor armature. In fact the whole is very much like a small motor. There is a small commutator and tiny brushes. A disk mounted at the end of the rotating coil shaft serves the purpose of retarding the motion of the coil so as to make the power proportional to the torque which causes the element to rotate. This disk is of metal (aluminum). It rotates

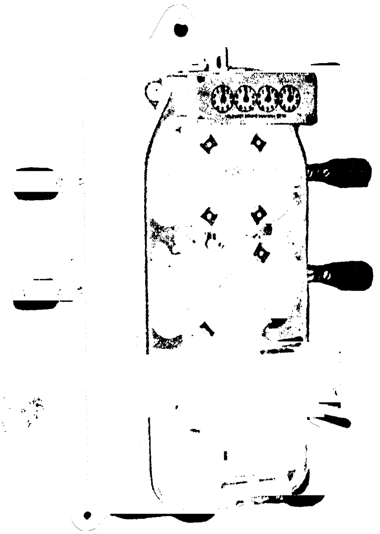


FIG. 221

between permanent magnets. Eddy currents set up in this disk are the cause of the retarding effect produced.

Compare Fig. 219 with Fig. 220 and try to identify in the latter the features suggested in the first illustration. Fig. 221 shows a three-wire watt-hour meter for use on three-wire circuits. Observe the two sets of coils, one set mounted above the other, an arrangement that makes for greater accuracy.

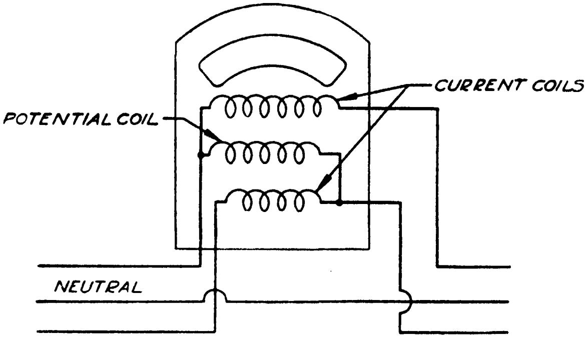


FIG. 222

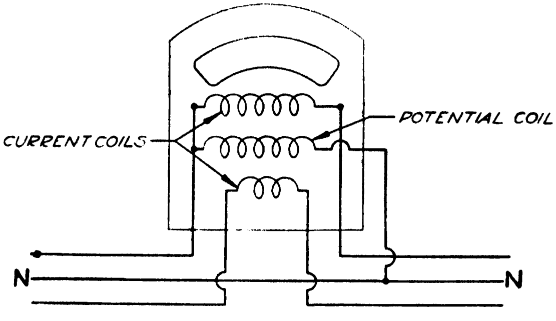


FIG. 223

Observe also, the single shaft with the retarding disk at the lower end.

The connections for the two-wire watt-hour meter are shown in Fig. 222, and for the three-wire meter, in Fig. 223.

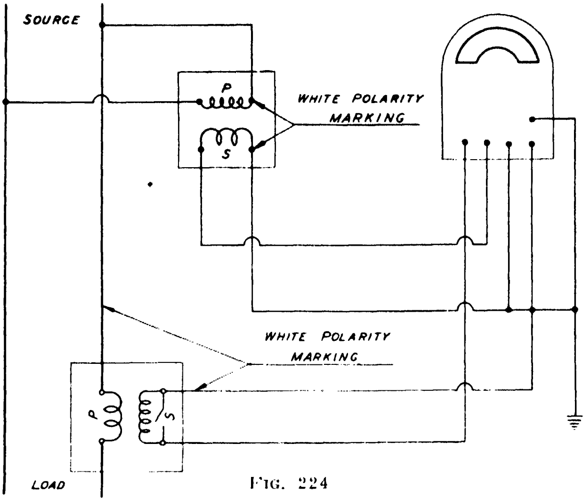


FIG. 224

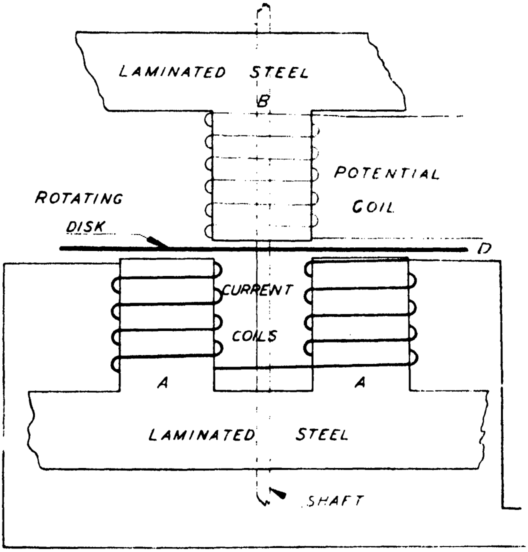


FIG. 225

Fig. 224 shows the use of a current and a potential transformer in connection with a watt-hour meter, on a high tension service line.

The induction type of watt-hour meter is today in very general use on alternating current circuits. It has no commutator. The shaft and the disk are the only movable parts.

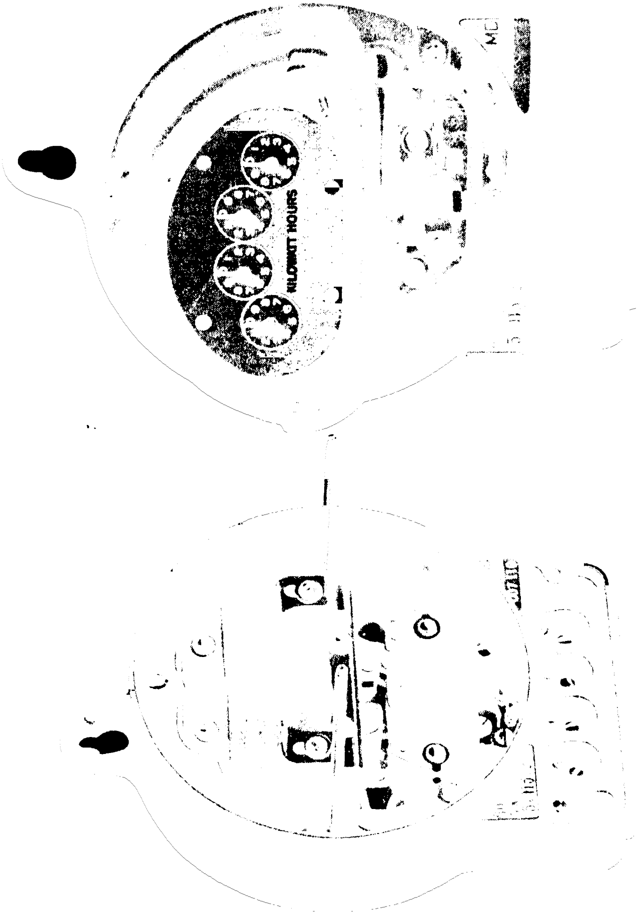


FIG. 226

In some models the disk has been replaced by a hollow cylinder. The construction is rugged and simple, and the operation is quite similar to that of an induction motor, the armature of which consists of the rotating disk and the field of which is produced by the current and potential coils of the instrument (see Fig. 225). This magnetic field is of course alternating, and in addition not only are the poles *A-A* of opposite polarity but pole *B* is out of step with *A-A*, because the current through the potential coil lags behind the current through the current coils. The constantly changing lines of force induce in disk *D* eddy currents, which react with the field poles *A-A* and *B* to produce motion of the shaft and disk (see Fig. 226).

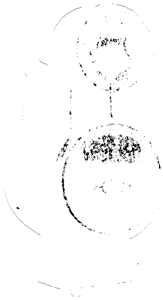


FIG. 227

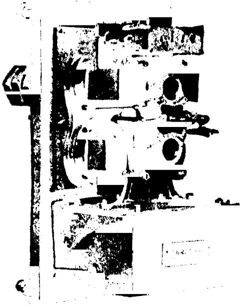


FIG. 228

48. PRE-PAYMENT WATT-HOUR METER, DEMAND METER:

To avoid the difficulty of collecting bills from transient consumers, power and light companies sometimes install prepayment watt-hour meters. One or more quarters are dropped into a coin slot (see Fig. 227) and the small crank is turned to make the meter ready to give service. The small dial at the top indicates how many "quarters' " worth of electrical energy still remain to the credit of the customer.

Power and light companies sometimes base their rates upon the ratio of the energy consumption to the maximum demanded by the customer. Watt-hour meters designed to measure not only the energy consumption, but also the maximum demanded by the customer, are called "demand meters." There are several types made. Some are based on the heating effect of the current, others are simply mechanical attachments or additions to the watt-hour meter that serve to record in some way the maximum current or power demand. Fig. 228 illustrates a demand meter operated by a motor wound clock. The wiring connections for this demand meter (two-wire system) are shown in Fig. 229.

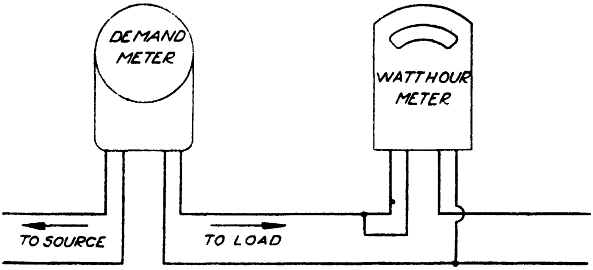


FIG. 229

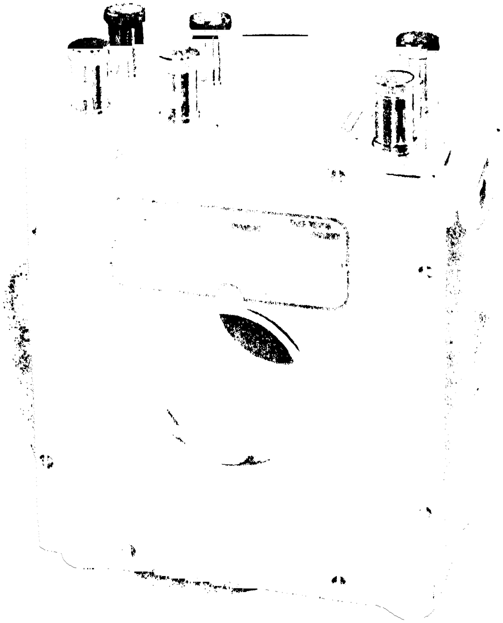


FIG. 230

49. INSTRUMENT TRANSFORMERS:

Meters are necessarily limited in their current and voltage ranges and capacities, as also in the ability of their insulation to withstand commercial voltages of high value. Transformers are needed to extend the ranges of ammeters and voltmeters. For best results such transformers are designed to be used with a given ammeter or voltmeter. A transformer designed to extend the current range of an ammeter is called a current transformer, shown in Fig. 230. A transformer designed to extend the voltage range of a voltmeter is called a potential transformer, shown in Fig. 231. Both of the instruments shown are of the portable type. The current transformer shown in Fig. 232, is intended for permanent mounting.

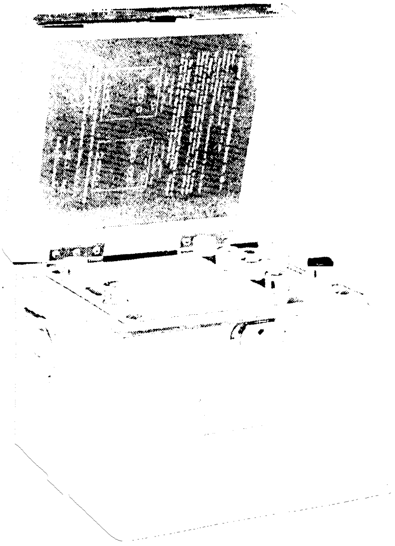


FIG. 231

The instrument transformer is built somewhat like the ordinary power transformer, but it requires very little power to operate. It consists of two coils, a primary and a secondary, wound on a laminated steel core.

The current transformer primary consists of a very few turns, in fact often of only one turn. Observe the Jewell current transformer in Fig. 233. The laminated core is made in two parts which are hinged so as to permit opening the core. In this way a line wire can be passed through the core and the current can be measured without any interrup-

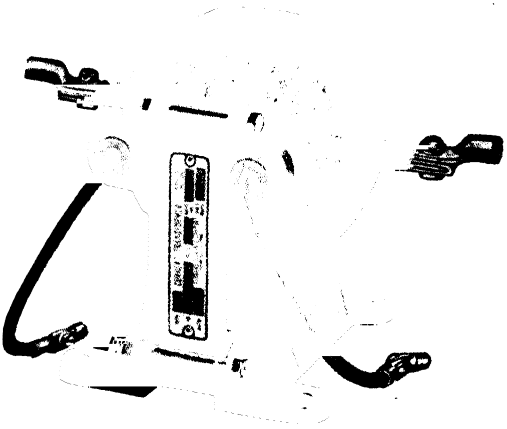


FIG. 232

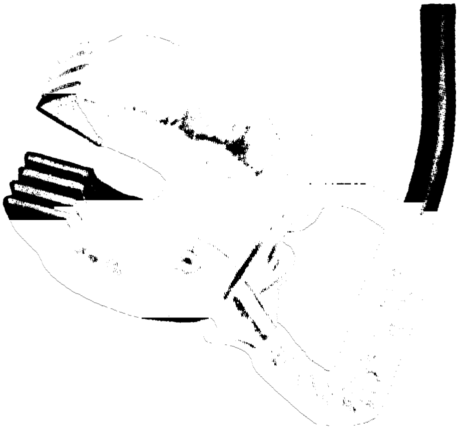


FIG. 233

tion to the service. Here the primary consists of the single line wire through the core.

The connections of the current transformer to line and ammeter are shown in Fig. 234. Observe the single pole short-circuit switch across the secondary coil of the current transformer. This switch is ordinarily mounted on the instrument itself. Its purpose is the protection to the apparatus and to the operator himself.

The current transformer reduces the current in proportion to the ratio of turns between primary and secondary.

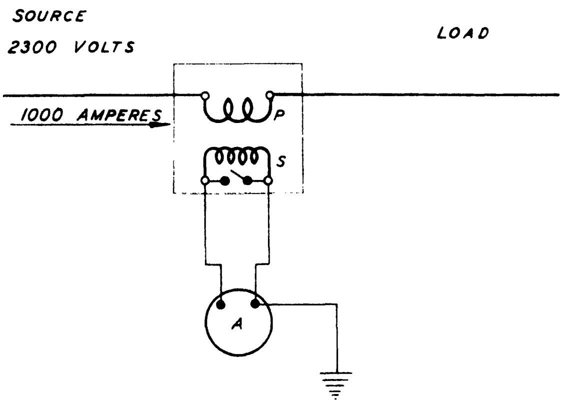


FIG. 234

If the secondary should be opened accidentally, the large "load" current through the primary would set up dangerously high voltages across the secondary terminals, so that both the operator and the instrument could suffer serious injury. NEVER OPEN THE SECONDARY CIRCUIT OF A CURRENT TRANSFORMER SO LONG AS THE PRIMARY SIDE IS ALIVE, UNLESS THE SHORT-CIRCUIT SWITCH IS CLOSED.

As a general rule manufacturers build instrument transformers for use with ammeters of 5 ampere range. The scale of the ammeter is then arranged to read the extended range values in accordance with the particular ratio of primary to secondary turns. Thus, for a ratio of 200 : 1, the scale reading would be 0 — 1,000 amperes.

Potential transformers intended for use on very high voltage circuits have their coils immersed in oil, partly for cooling purposes, but more particularly to insure good insulation qualities. For the lower voltages such as 2,300, 4,600, they are used dry. Frequently the primary coil is built in two similar sections, which can be joined either in series or in parallel by means of special links. This affords two ranges in one instrument. Potential transformers are, in general, designed for use with 110 volt range voltmeters. The connections of a potential transformer to the line and the voltmeter are shown in Fig. 235. Observe that the primary of the potential transformer has many turns and the secondary few turns. Observe also that the secondary side is grounded as an added protection to the operator. This is also done in the case of the current transformer. Current and potential transformers when used with wattmeters are connected as shown in Figs. 236 and 237.

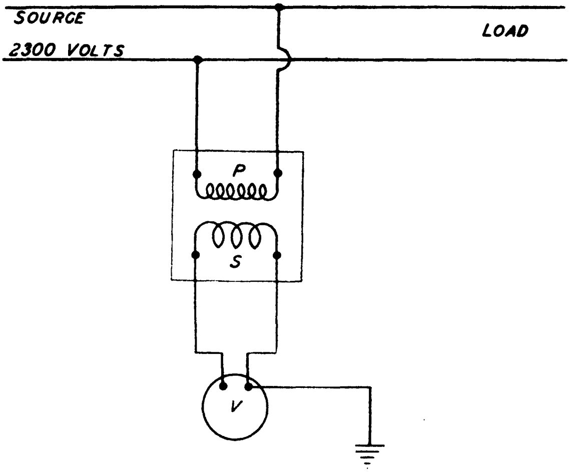


FIG. 235

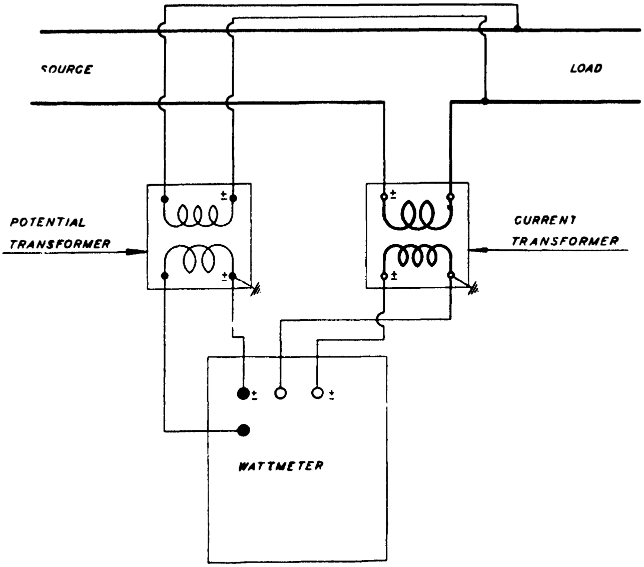


FIG. 236

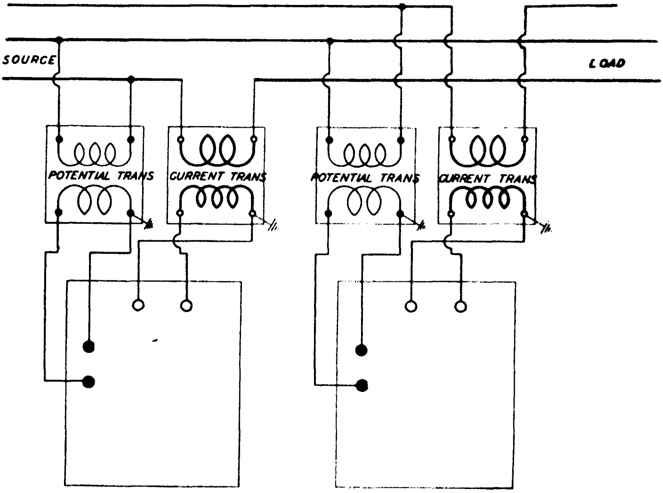


FIG. 237

50. THE SYNCHROSCOPE:

It is the general practice in power plant operation to connect several alternator units in parallel across common busbars.

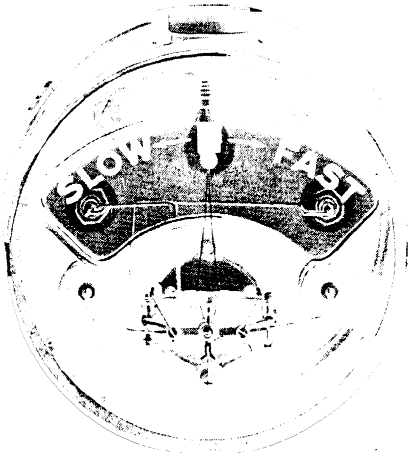


FIG. 238

Certain conditions must be attained to do this: the voltages must be the same, the frequency must be the same, the phase rotation must be the same. Frequency and phase rotation conditions may be determined by use of synchronizing lamps, or by use of a synchroscope. (For explanation refer to the section on Synchronizing.)

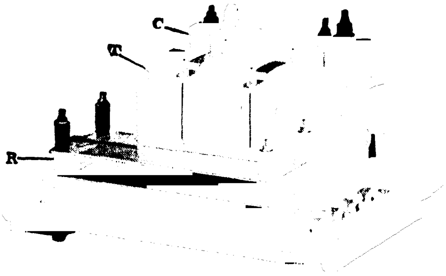


FIG. 239

The Weston synchroscope (Fig. 238), embraces the general features of design and construction of the Weston wattmeter. Both movable and fixed coils are wound with fine wire. The scale is translucent (glass) illuminated from behind the pointer by a lamp which reaches full brightness when the two voltages have the proper relation to each other. This lamp operates at a low voltage from the secondary of a specially constructed transformer, which has two primaries, one connected to the busbars, the other to the machine about to be connected to the busbars. When the busbar voltage and the incoming machine voltage are in opposition the lamp remains dark. For correct conditions of the two voltages the shadow of the pointer will be seen through the glass scale at the center of the black spot shown in Fig. 239. The transformer as well as a condenser and resistances are assembled in a separate unit external to the synchroscope itself and are encased ready for switchboard mounting, as shown in Fig. 240. Another view of the synchroscope is shown in Fig. 241. The connections are shown in Fig. 242. When the lamp is dark the pointed image cannot be seen, since no shadow is thrown. Hence the pointer shadow is only seen at the center of the black spot when the two voltages are in proper phase agree-

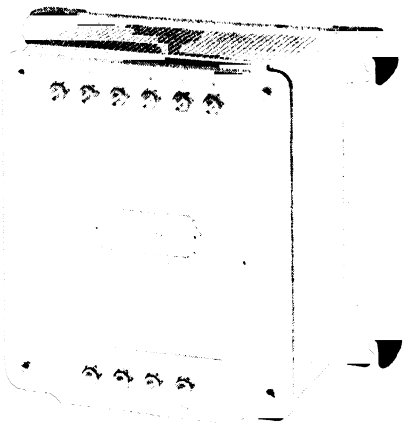


FIG. 240

ment and when the frequency of both is the same, since under these conditions the lamp is brightest. It is then that the incoming machine may be connected to the busbars without damage to itself or to other station equipment.

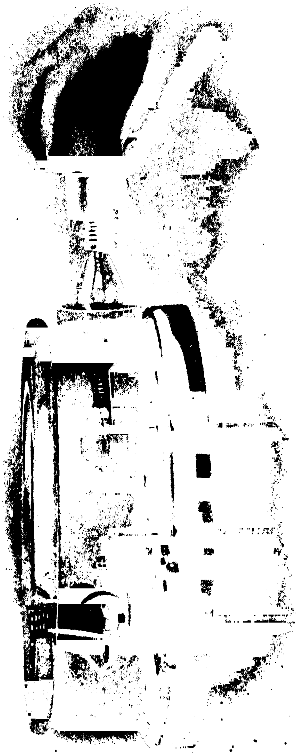


FIG. 241

51. THE POWER FACTOR METER:

It is highly desirable to know the power factor at which alternating current equipment is being operated. Of course, power factor (cos Φ) can be calculated, but an instrument for directly indicating the power factor not only saves time, but can be made to give a permanent record graphically.

In Fig. 243 the complete movement of a Weston power factor meter is shown. Observe that it is a dynamometer type of instrument. Fig. 244 is like the preceding picture except that the two field coils have been removed thus revealing the movable coil construction. Note that there are two movable coils mounted on one shaft at right angles to each other. There is no mechanical spring arrangement to return the movement to one end of the scale, and so the pointer can remain at any point on the scale.

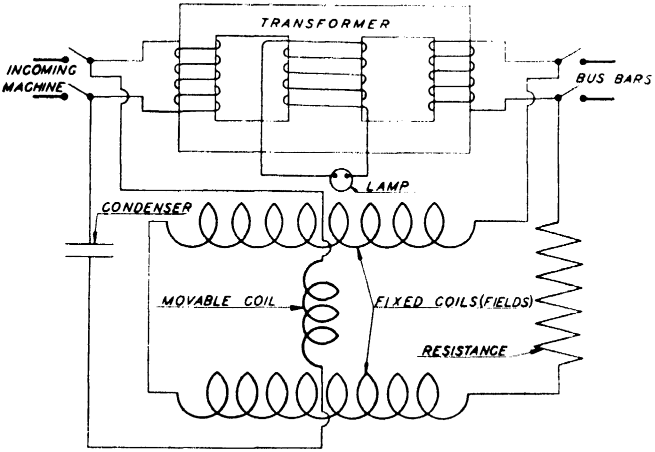


FIG. 242

The operation of the Weston power factor meter is based upon the fact that a resistance load current is in phase with its voltage, whereas an inductive reactance load carries a current 90° E. behind its voltage. The two potential coils of the instrument mounted at right angles to each other are connected respectively in series with a resistor *R* and a reactance coil *L* shown in Fig. 245.

The pointer is mounted in the plane of potential coil *Z*. When the two potential coil circuits are connected across the line wires (110 volts) the current in coil 2 lags approximately 90° E. behind the current in coil 1, the value of *R* and *L* having previously been adjusted to the proper values by the

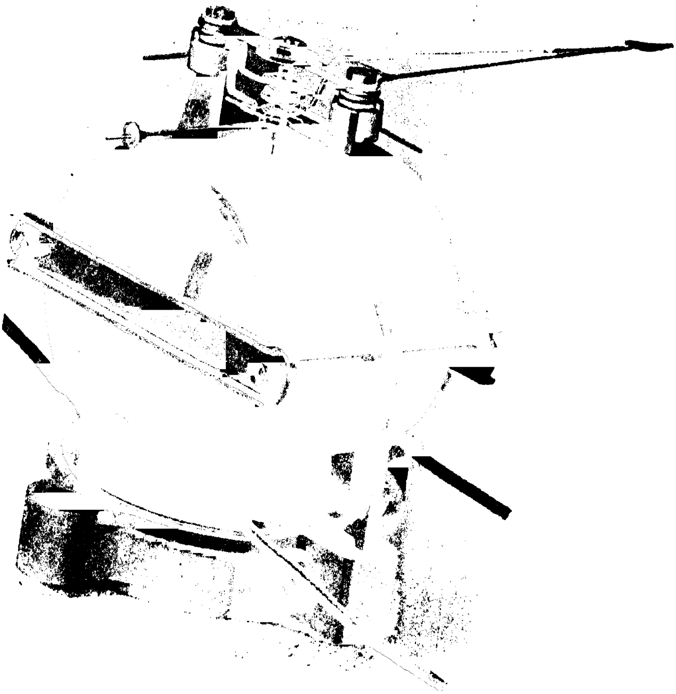


FIG. 243

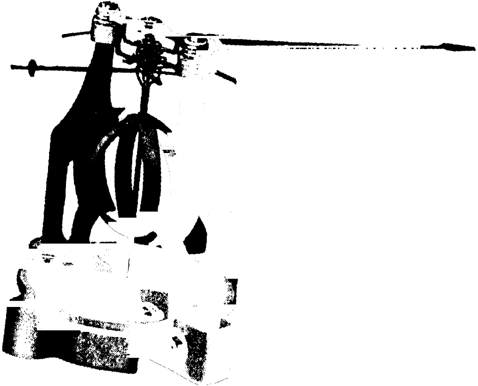


FIG. 244

manufacturer. The magnetic field due to the current in each potential coil tends to align itself with the magnetic field produced by the main field coils. Hence coil 1 tends to produce rotation in one direction, and coil 2, in the opposite direction. The pointer comes to rest at the place where these two forces balance each other.

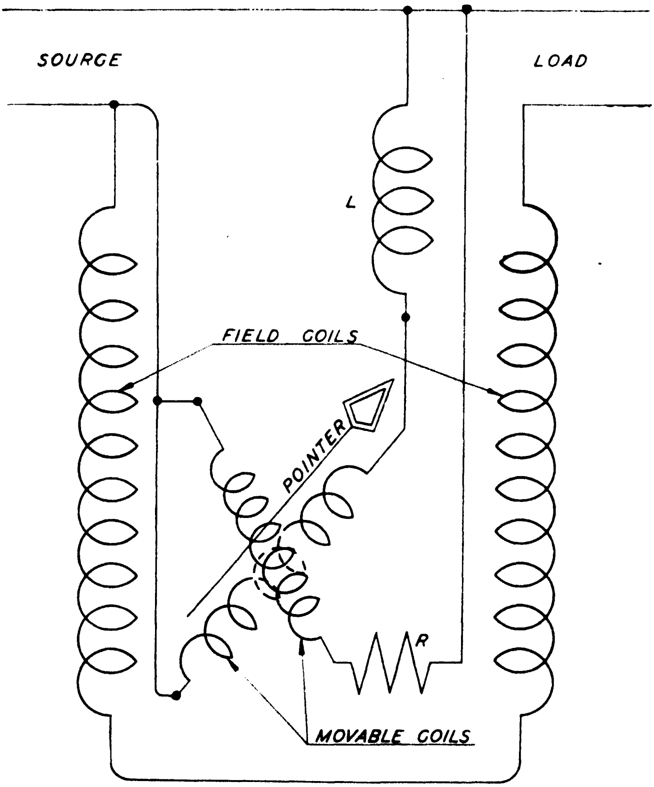


Fig. 245

Observe in Fig. 246, that a power factor of unity (or 1.00) is indicated at the center of the scale and that power factor decreases both to the right and to the left. Deflection to the right indicates leading current, deflection to the left indicates lagging current.

The two-phase power factor meter differs from the single-phase instrument just described only in that no inductance coil *L* is needed in series with potential coil 2, because the current in phase 2 of a two-phase circuit is by nature 90° E. behind the current in phase 1. Potential coil 2 is connected across phase 2 voltage, and potential coil 1, across the voltage of phase 1.

In the three-phase instrument the pointer is mounted so as to make equal angles with the planes of the two potential coils 1 and 2. Hence it is placed midway between the planes of these coils. The connections for the three-phase instrument are shown in Fig. 247. The current or field coils are connected in series with one of the line wires, and the two potential coils are connected respectively between this wire and one of the remaining line wires.

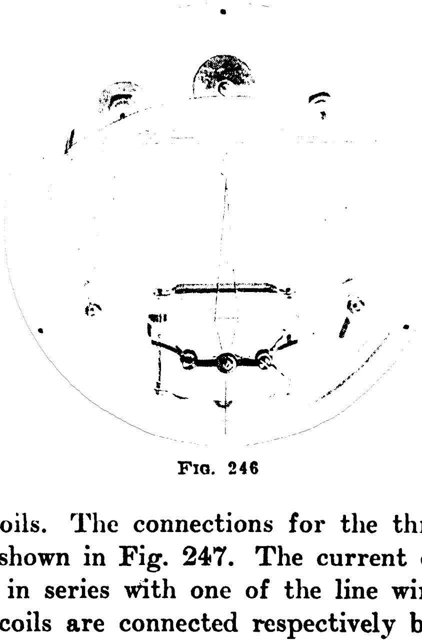


FIG. 246

The power factor meter measures the true power factor in balanced two- and three-phase circuits. If the circuit is unbalanced with respect to power factor, that is if the phases differ in character of load, then the power factor meter indicates the power factor in the line in which the current coil is inserted. This value is very probably not true for any one phase, but is a sort of averaging of the conditions in the three phases.

52. THE FREQUENCY METER:

One of the most important measuring instruments in the central station is the frequency meter. Electrical apparatus is designed to operate at certain standard frequencies. The speed of alternating current motors depends upon the frequency of the voltage source. Hence it is desirable to maintain station frequencies fairly constant. Frequency meters

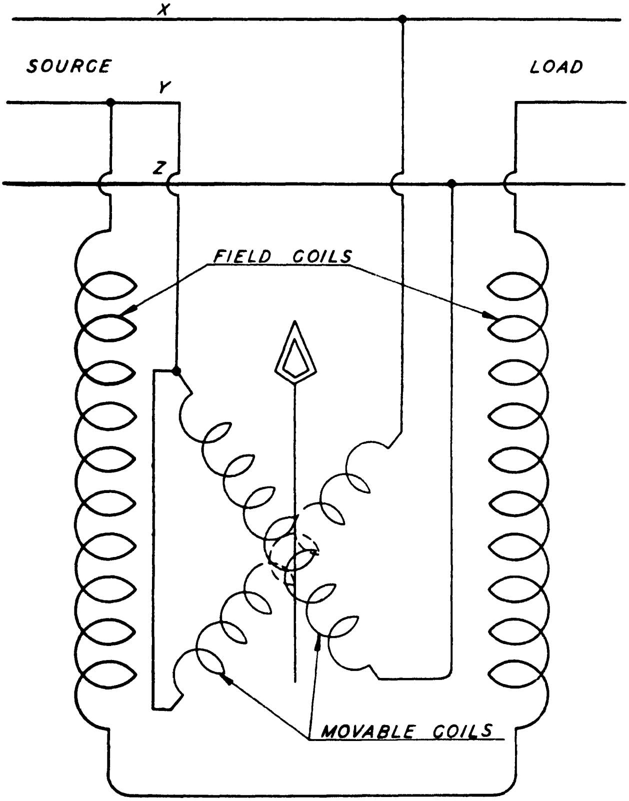


FIG. 247

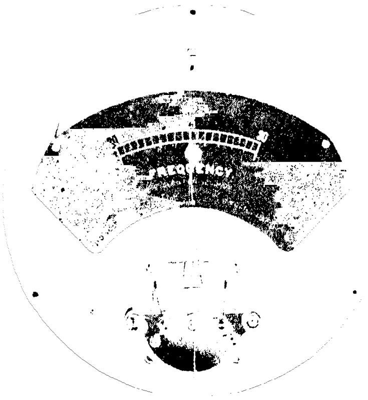


Fig. 248

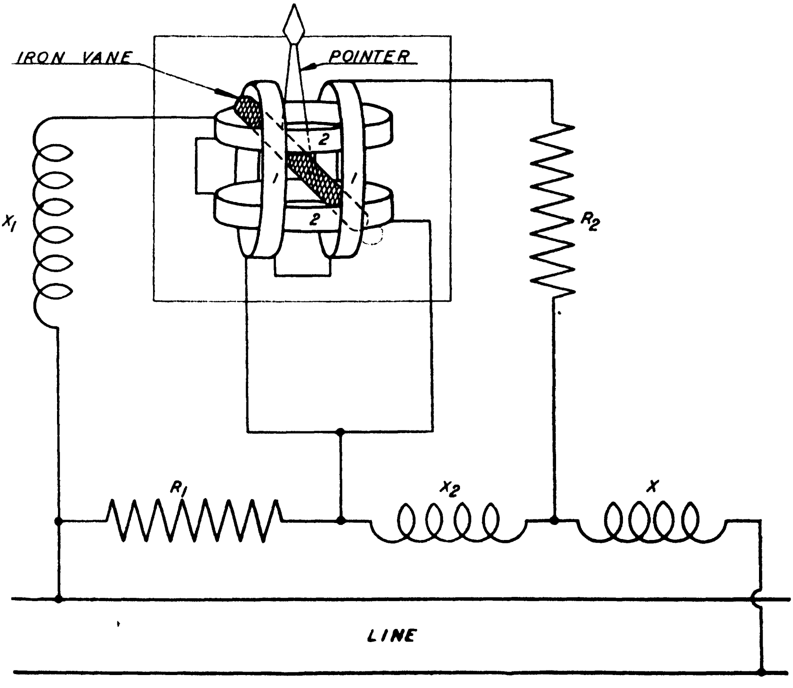


Fig. 249

are built for use on standard commercial frequencies such as 25 cycles or 60 cycles; or they are designed for use on radio frequency circuits in which frequencies of the order of hundreds of kilocycles (1,000 cycles) are encountered.

Fig. 248 shows a Weston switchboard type frequency meter. It consists of two field coils fixed rigidly at 90° to each other. One is slipped inside the other. The movable system consists of a thin iron vane mounted on the shaft. The vane can move freely within the coils and tends to align itself with the composite magnetic field produced by the two field coils.

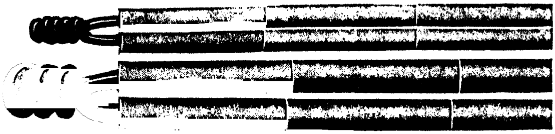


FIG. 250

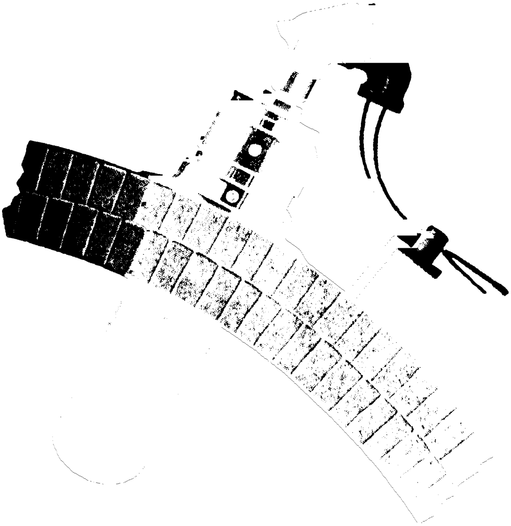


FIG. 251

In the normal position, the iron vane, the coils, and the pointer which indicates the proper frequency on the scale are placed as shown in Fig. 249, which also shows complete connections.

53. PYROMETERS:

High temperature measurements are made by means of pyrometers. Though there are several kinds of pyrometers available, those employing the thermocouple principle are most common. The metals generally used are bismuth, antimony, platinum, rhodium, nickel, chromium, and alloy combinations of these metals. By use of thermocouples, voltages as high as

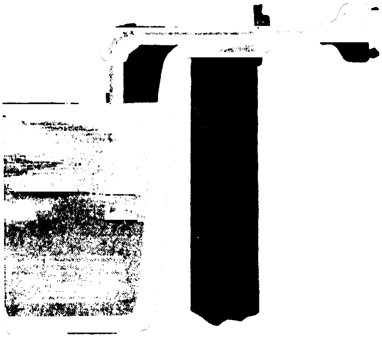


FIG. 252

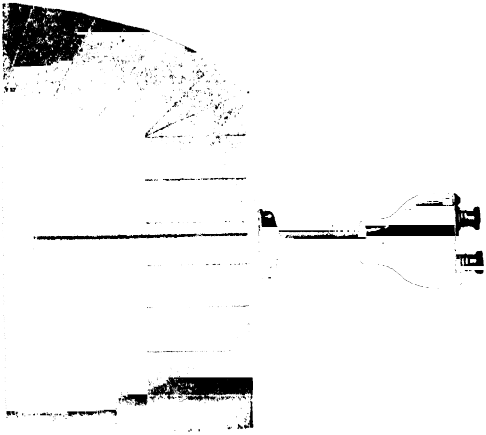
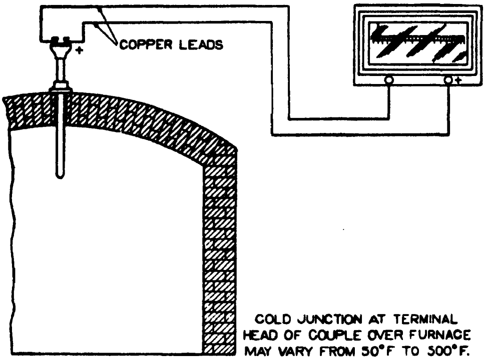


FIG. 253

50 millivolts are developed. The temperatures measured range from under 1,000° F. to 3,000° F. and even higher. Fig. 250 shows different sizes of thermocouples and the protecting porcelain insulating tubes. Fig. 251 shows a thermocouple inserted into a kiln through its crown on top. Fig. 252 shows a thermocouple inserted into molten metal, and Fig. 253 shows a thermocouple installed in a furnace.



COLD JUNCTION AT TERMINAL HEAD OF COUPLE OVER FURNACE MAY VARY FROM 50°F TO 500°F.

FIG. 254

The simple wiring diagram of one form of pyrometer made by the Brown Instrument Company of Philadelphia is shown in Fig. 254.

The electrician is of course more especially concerned with the problem of installation, that is, of the actual wiring involved in a pyrometer installation. Figs. 255, 256 are examples of wiring installations involving thermocouples, an indicating instrument for the use of the operator, and a recording instrument for permanent data and for the engineering office. The former method is preferable because of its relative freedom from ground and short-circuit troubles. Observe that in Fig. 256 a common return wire is used, whereas in Fig. 255 each thermocouple is included in a separate electrical circuit.

The indicator, see Fig. 257, is in reality a direct current (permanent magnet movable coil) millivoltmeter. Fig. 258 shows a typical example of a simple installation. The pyrometer and thermocouple illustrations all represent the Brown Instrument Company products.

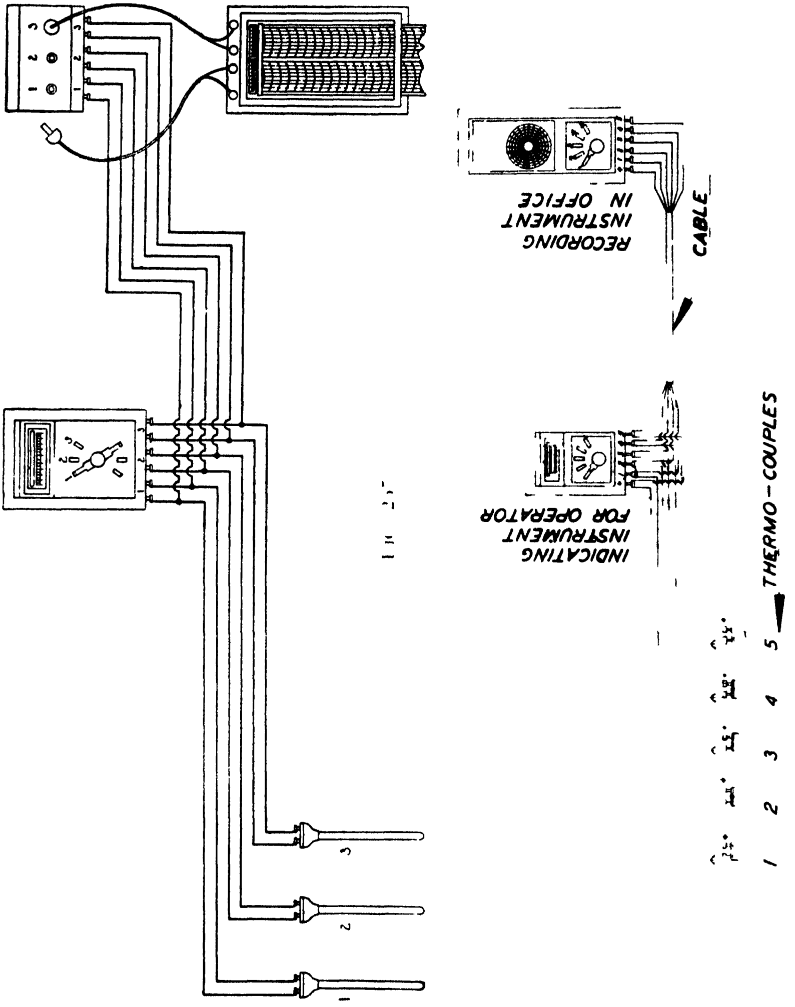

RECORDING INSTRUMENT IN OFFICE
CABLE
INDICATING INSTRUMENT FOR OPERATOR
THERMO-COUPLES
1
2
3
4
5

Fig. 256

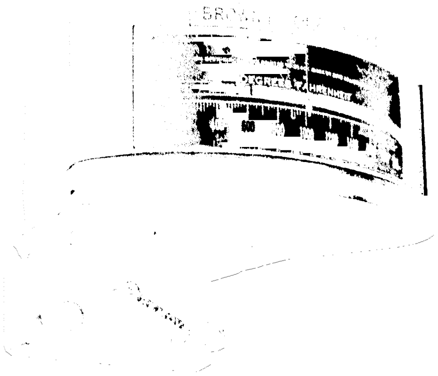


FIG. 257

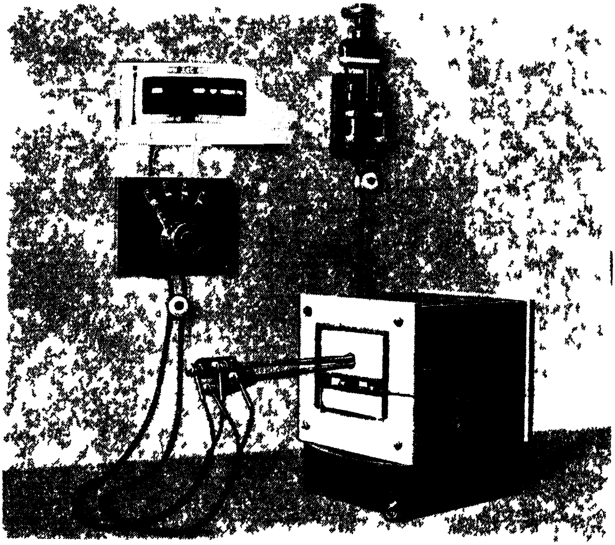


FIG 258

CHAPTER VI

SINGLE-PHASE MOTORS

54. DIFFERENT KINDS:

In many communities single-phase motors are limited as to size. Power companies object to sizes larger than 15 horsepower. Among the reasons for this objection are unbalancing of the three-phase supply, flickering of lights due to larger starting currents and resulting voltage drops, unsteady flow of power as contrasted with the three-phase motor, greater cost of the single-phase unit per horsepower capacity.

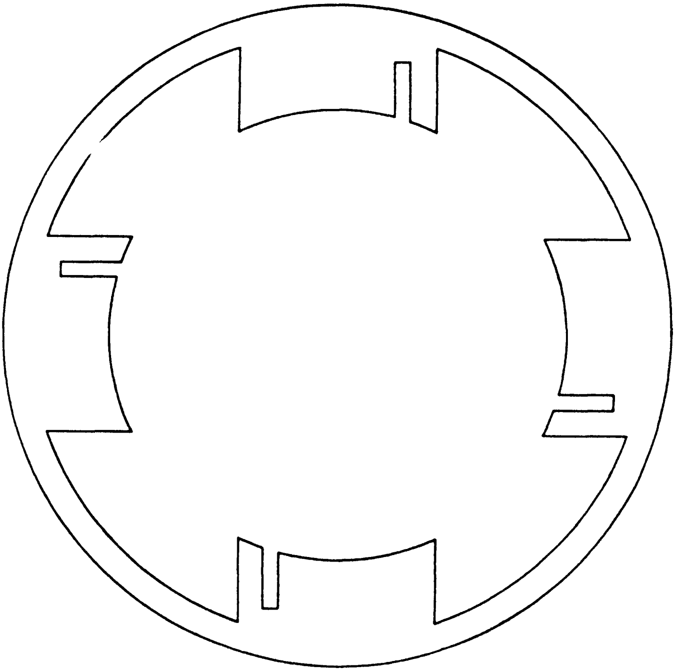


FIG. 259

Hence single-phase motors are usually relatively small motors. In fact, by far the larger number of fractional horsepower motors are single phase. For washing machines, fans, vacuum cleaners, small pumps and grinders, or other rotating devices necessitating only a very small amount of power, the single-phase motor is well fitted.

Single-phase motors all have some arrangement, either electrical or mechanical, which, at the moment of starting, enables the motor actually to turn over. Without such a device, the single-phase motor (except series) would not turn over even though the line switch be closed. This leads us to a consideration of the various kinds of single-phase motor classified according to means used for getting the motor started: shaded pole motor, split-phase induction motor, repulsion motor, repulsion-induction motor, series motor. Each is discussed in detail in a section following.

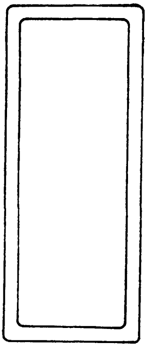


FIG. 260

55. SHADED-POLE SINGLE-PHASE INDUCTION MOTOR:

One of the early types of commercial single-phase alternating current motors was the shaded pole induction motor. The stationary portion of this machine was built like the frame of a direct current motor, except that a narrow slot was cut across the pole face near the end of each pole piece. See Fig. 259. The purpose of the slot was to accommodate a short-circuited winding called a shading coil. Ordinarily this winding was made of a solid copper bar that was soldered or welded at the joint to insure good electrical connection (Fig. 260). In shape it was rectangular. In addition to the shading coil, each pole piece was, of course, equipped with a winding made of a number of turns of small sized insulated copper magnet wire. See Figs. 261-262. The construction and appearance was like the field winding of a direct current motor. There was no electrical connection between the shading coil and the other winding. Also, there was no connection between the shading coil of one pole and that of another pole. The coils made of magnet wire or the field coils proper were connected together to form a current-carrying circuit, the purpose of which was to set up north and south poles like in a direct current motor.

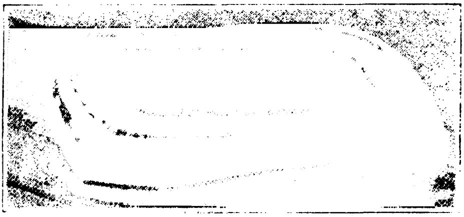


FIG. 261

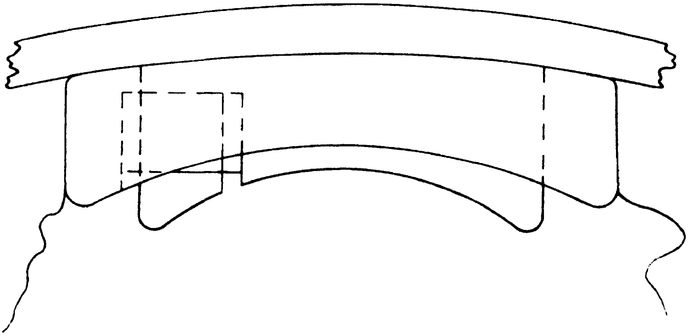


FIG. 262

The rotating element or the rotor is very simple in construction. It has what is known as a squirrel-cage winding. The rotor consists of a shaft on which is mounted a laminated iron or steel core. The slots that hold the winding may be round or rectangular, and they may have a small opening along the full length of the slot on top, or there may be no opening at all. The winding is not fed through the opening of the slot, if there is one, but rather the solid copper bars that make up the winding are pushed through from one end. One solid, bare copper bar or rod is set into each slot. The bar is not insulated from the core, but fits snugly in the slot, without insulation. The ends of the copper bars are fastened to copper rings, one on each end of the core. Formerly the bars were riveted to the ring and then soldered to insure a good electrical connection. Welding the bar to the ring is a more modern process and makes for a more secure electrical and mechanical connection. Care must be exercised in making the connection between bar and ring secure, because of the large amount of current circulating in the winding. A poor connection will cause excessive heating of the bars and rings, which may make necessary the rebuilding of the rotor. A still more recent method of placing the squirrel-cage winding is to cast the bars and rings into place. The squirrel cage is then one solid piece of metal, usually aluminum.

The magnet wire winding of the motor is connected across the line wires and has line voltage impressed upon it. This is called the primary winding or field winding. There is no electrical connection between the primary and the rotor which is called the secondary. The current in the secondary winding is set up by induction.

The purpose of the shading coil is to begin the rotation of the rotor which will not start due to its own action. The action of the shading coil is as follows. Assume an alternating current to pass through the field winding, when the shading coil is removed. The current passing through the winding sets up lines of force, which we may assume to be equally distributed over the surface of the pole face. See Fig. 263. Even though the direction of the lines of force changes with each reversal of current, the lines of force remain equally distributed. This is true for each pole, regardless of the number of poles in the motor. When the lines of force are equally distributed, the rotor is unable to start rotating, because the stator field poles are counterbalanced by similar poles on the rotor. Current through the rotor bars produces magnetic poles in the rotor iron and these are directly opposite the stator poles and are of like polarity. See Fig. 263. The interaction of these poles results in a force acting directly in line with the center of the shaft. Hence the rotor is pushed downward against the bearings but is not turned over. There is no torque or turning effect.

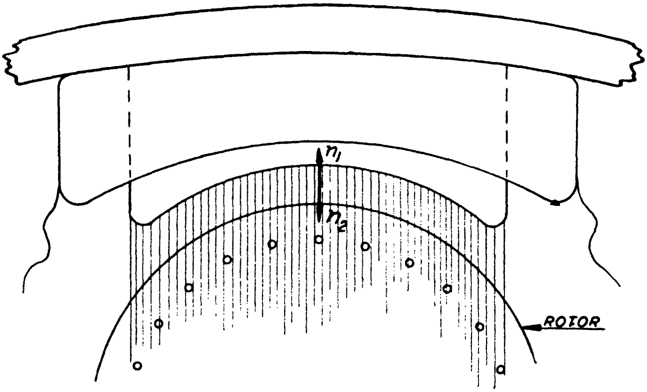


FIG. 263

Now pass an alternating current through the primary winding with the shading coils in place. It will be noted that instead of the lines of force being equally distributed over the whole pole face, one portion of the pole face is densely covered with lines of force, while that portion of the pole face having the shading coil shows relatively few lines. Some of the lines of force from the primary winding are cut by the shading coil. When a conductor cuts lines of force, there is set up in that conductor an E.M.F. The shading coil being of low impedance and being short circuited, has a large current induced in it, which current in turn sets up lines of force through the shading coil that are opposite in direction to the lines of force set up by the primary winding. The result of this opposition is neutralization in that region. Consequently there will be an unequal distribution of lines of force on the pole face. See Fig. 264. Distorting the path of the primary lines of force shifts the force causing rotation of the rotor to one side of the center line. It is obvious that the force between N_1 and N_2 is not in line with the shaft. Hence there will be rotation in a given direction as shown. The effect is in reality equivalent to hold back the primary lines of force from the shaded area of the pole face, so that the flux reaches its maximum first at the right of the pole face area and then sweeps across to the other side by the time that the current in the shading coil has dropped to zero.

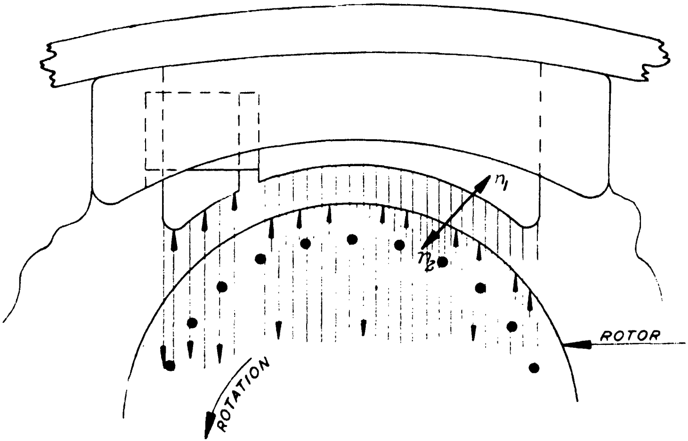


FIG. 264

Once the rotor has reached full speed, the shading coil has played its part and it is no longer needed. The rotor bars are now cutting the lines of force and are inducing current which sets up lines of force in the rotor core, which, reacting with the field poles, keep the rotor turning. The construction of the motor, however, does not permit the removal of the shading coil after the motor is running and there is no way of disconnecting it. Hence it must remain in the motor at all times. Even though it offers a means of starting the motor, it does so at the expense of reducing the efficiency of the motor during the running period.

Some manufacturers placed the slot at the center of the pole face (Fig. 265) instead of nearer to one side. This permitted a reversal of the direction of rotation which was accomplished by placing the shading coil over the other half of each pole.

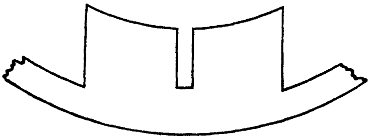


FIG. 265

Although the shaded coil motor is obsolete and is no longer manufactured, nevertheless, some are still to be found in use. Its simple construction makes possible an easy introduction to the understanding of the single-phase induction motor.

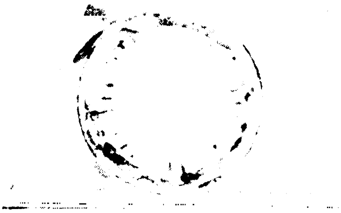


FIG. 266

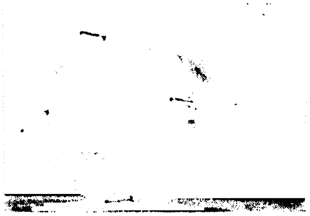


FIG. 267

56. THE SPLIT-PHASE MOTOR:

This motor retains the essential principles of the shaded pole motor but utilizes them somewhat differently. The split-phase motor is so called because it attempts to produce two phases in a machine by use of current from a single-phase line.

It is made in two distinct styles: one in which the primary or field windings are placed on the stator; the other, in which the field windings are placed on the rotor. In the first type, the stator (Fig. 266) consists of a laminated iron or steel core, having large and deep slots to accommodate two separate and distinct field windings. See Figs. 267, 268, 269. One of these is called the "starting winding," the other, the "running winding." The two windings are insulated from each other and are placed in slots 90° E. apart. The running winding is in service so long as the motor is running or is connected to the line.

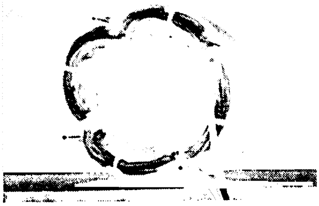


Fig. 268

Fig. 269

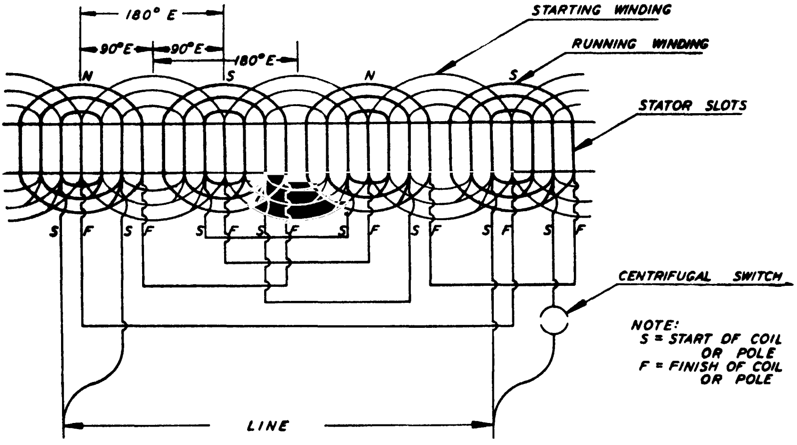


Fig. 270

The starting winding, as its name implies, is in service only for a few moments, or during the time that the motor requires to come from standstill to full speed.

A comparison of the starting and running windings shows that the former is made of a number of turns of small-sized, insulated (cotton or silk) magnet wire placed in a number of slots. The running winding is made of a larger size insulated magnet wire and has more turns of wire per pole. This winding is also placed in a number of slots and is arranged to produce definite field pole areas. The two windings have a displacement of 90° E. The number of slots into which the running or starting winding is distributed, depends on the total number of slots divided by the number of poles in the motor. Fig. 270 shows the two windings in place in a stator.

Fig. 271

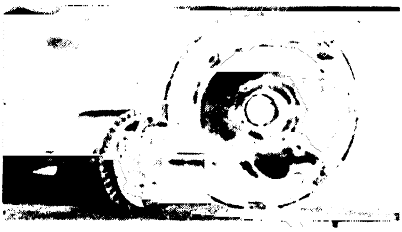


Fig. 272

The poles become alternately north and south as the current alternates.

Should the starting winding remain in the circuit for more than three or four minutes, it would heat up excessively. The starting winding overlaps the running winding at different places so that there would be possibility that the heat from the starting winding would scorch the insulation on the other winding. Because the starting winding may remain in the circuit only for a comparatively short period of time, it is necessary to use some kind of device for opening the starting winding circuit. Ordinarily a centrifugal switch is used to open and close the starting winding circuit. The design of the switch varies with different makes of motors. However, the principle of operation and the connection is usually the same. The switch is always connected in series with one of the leads feeding the starting winding. One type of centrifugal switch consists of a split brass or copper cylinder mounted on an insulator (usually fiber). The insulator is fastened to an end bracket of the motor. See Figs. 271, 272.

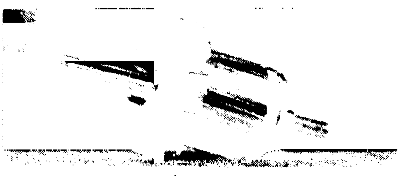


FIG. 273

Two or three small metal brushes (brass or copper) are mounted on the rotor (Fig. 273). A small spring pulls the brush down to the split cylinder and provides a means for good contact between the brush and the cylinder. See Fig.

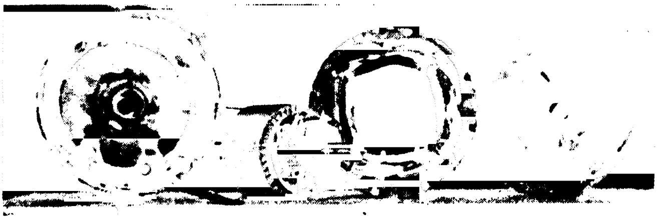


FIG. 274

274. When the motor is at rest or when the speed is below a definite value, the brushes make contact with the split ring and the starting winding circuit is closed. Centrifugal force acting on the brushes forces them away from the cylinder and so opens the starting winding circuit as the motor is approaching full speed.

A split-phase motor will not begin rotation without a starting winding. It can be made to run by turning the rotor rapidly by hand and then closing the line switch, but this is not a practical method. The motor will then run in the direction in which the rotor is turned. Without a starting winding the lines of force are evenly distributed over the pole face area, setting up a balanced condition as in the shaded pole motor operating without a shading coil. See Fig. 275. And as in the case of the shaded pole motor the rotor is unable to turn in either direction, but remains in one position and produces a humming sound. The starting winding takes the place of the shading coil and produces the same sort of effect, except that it does so by current taken from the line rather than by an induced current.

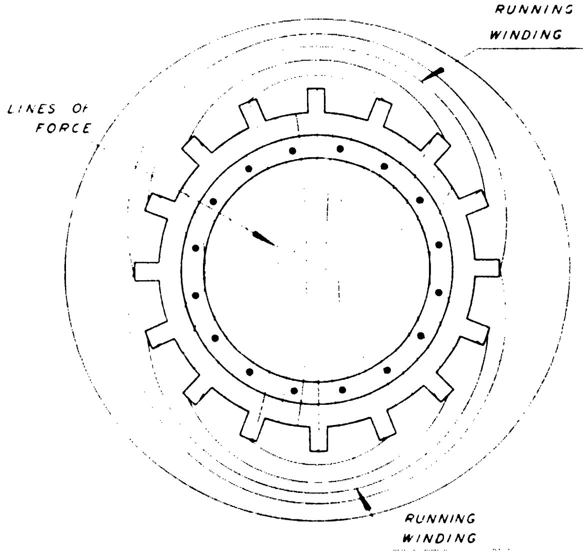


FIG. 275

When the line switch is closed, current flows through both starting and running windings. Because the running winding has more turns and consists of heavier wire, its resistance may be smaller but its reactance is greater than the resistance and reactance respectively for the starting winding, since the latter consists of fewer turns and finer wire. Therefore, the currents through the two windings are not in phase with each other. The current through the starting winding is ahead of that through the running winding. If the two currents were in phase, then both windings would produce poles on different parts of the stator surface at the same time. See Fig. 276. But since the starting winding current is ahead of the running winding current, the pole *n* is produced ahead of the pole *N*; similarly *s* is produced ahead of *S*. Also during the second half of the current cycle, the polarity of all poles changes, the *n* pole having shifted to the former *s* position, followed in proper phase interval by a shift of the *N* pole to the former *S* position. Apparently then the double winding causes what seem to be two-phase currents, and these produce magnetic fields out of step. Each pole seems in turn to occupy the positions 1, 2, 3, 4. In other words the poles seem to rotate along the surface of the stator. Now, with the current flowing also in the rotor, the latter too becomes magnetized, and the revolving field poles in the stator may be thought of as dragging the rotor poles around after them, thus causing rotation. A more detailed explanation of a revolving field is given in the chapter on polyphase motors.

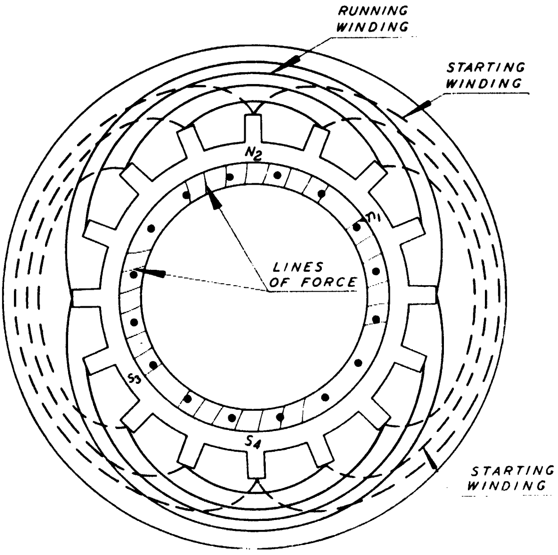


FIG. 276

A vector picture would perhaps show more clearly the condition of the currents in the two windings. See Figs. 227, 278, 279. We assume that for the running winding the resistance is r and the reactance $= X$. For the starting winding the resistance is R, and the reactance x. Then the currents I_s and I_R both lag behind the line voltage E, but not by the same angles. The angle Φ_r is greater than the angle Φ_s.

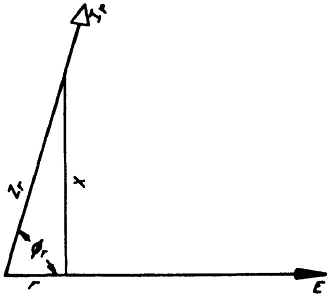


FIG. 277

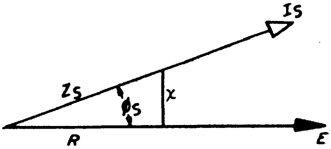


FIG. 278

The positive direction of the current in the starting winding with respect to the positive direction of the current in the running winding determines the direction of rotation of the motor. If the positive direction of the current in the starting winding is the same as in the running winding, the rotation of the stator poles is in one direction and the rotor turns in that direction. Reversing the leads of the starting winding reverses the positive direction of the current through it, the

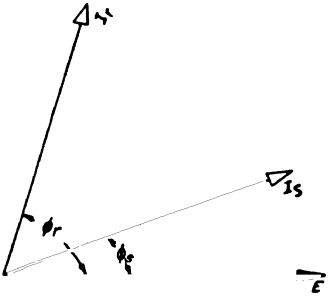


FIG. 279

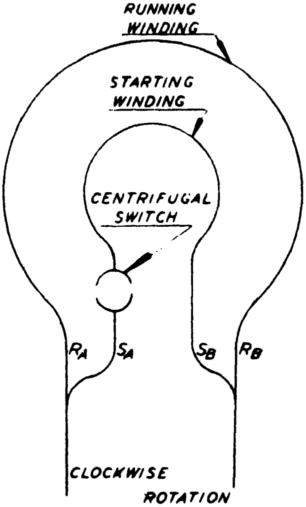


FIG. 280

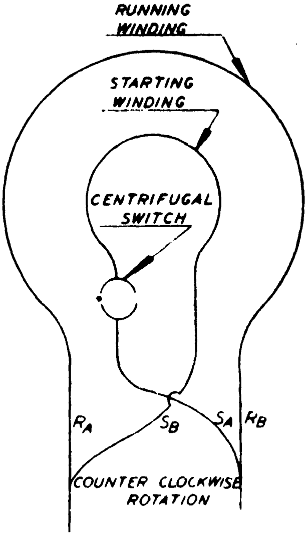


FIG. 281

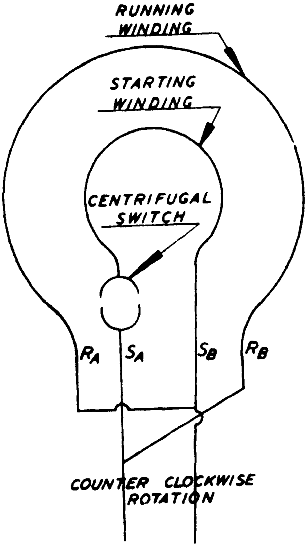
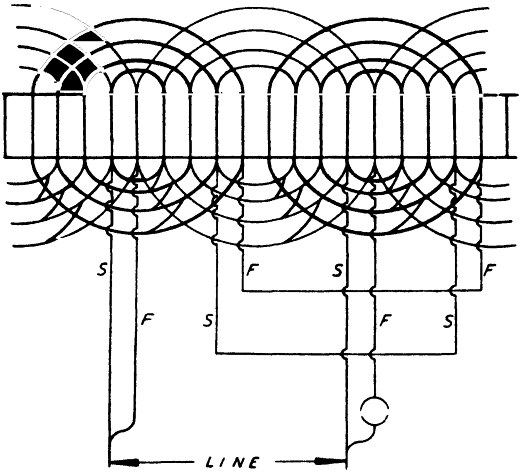


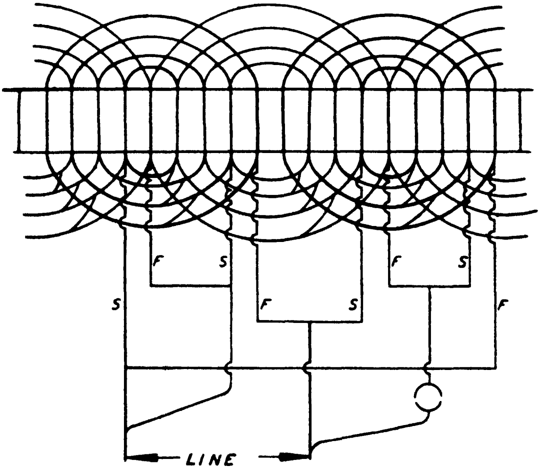
FIG. 282

result being the changing of the direction of the rotation of the poles around the stator and hence also the direction of rotation of the rotor. Therefore in order to change the



SINGLE CIRCUIT CONNECTION FOR MAXIMUM VOLTAGE.

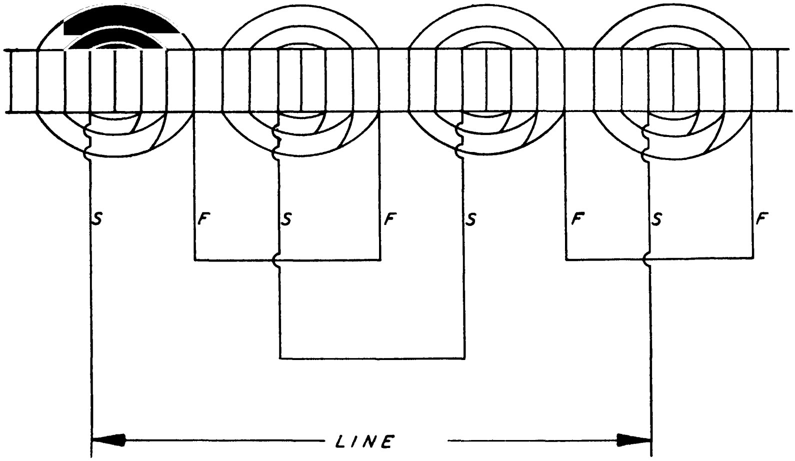
FIG. 283



TWO CIRCUIT CONNECTION FOR ½ MAXIMUM VOLTAGE

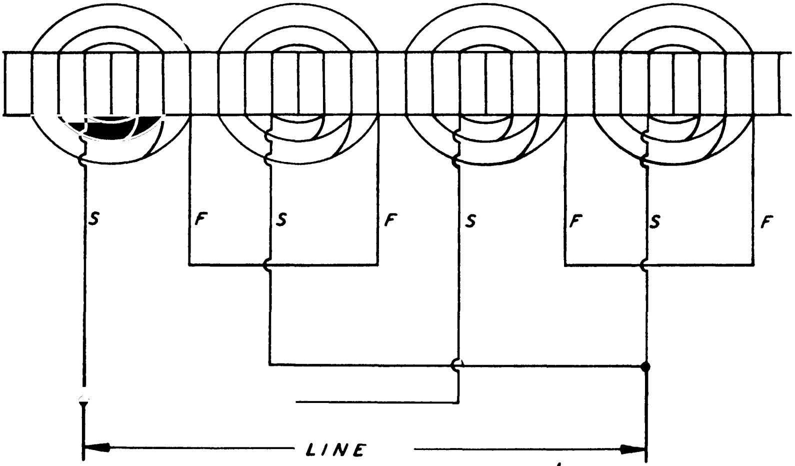
FIG. 284

direction of rotation of a split-phase motor, all that is necessary is to reverse the starting winding leads or to reverse the



4 POLE SINGLE CIRCUIT CONNECTION FOR MAXIMUM VOLTAGE

FIG. 285

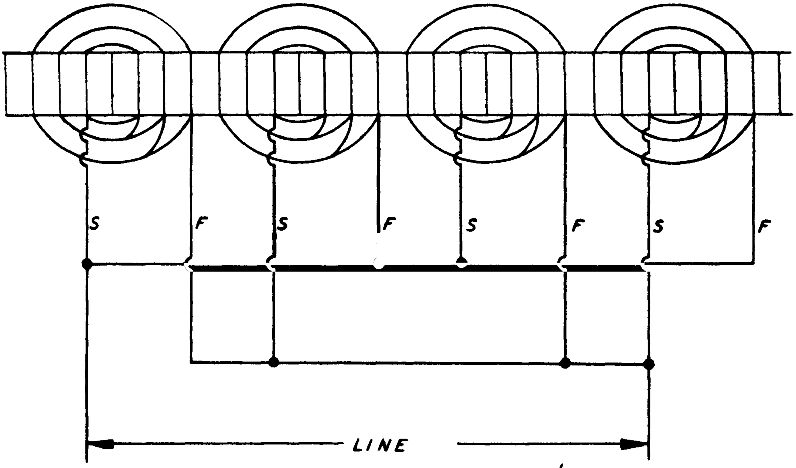


4 POLE, 2 CIRCUIT CONNECTION FOR ½ MAXIMUM VOLTAGE

FIG. 286

running winding leads. Reversing the line wires, or both starting and running winding leads, will not produce a reversal of rotation. This is shown in the three illustrations, Figs. 280, 281, 282.

In a split-phase motor the starting winding like the running winding is either single-circuit, or two-circuit, in kind. If the running winding is connected single-circuit, the starting winding is also connected single-circuit. If the running winding is connected two-circuit, the starting winding is also connected two-circuit. Figs. 283, 284 illustrate a single- and a two-circuit connection respectively, for a two pole split-phase motor. Single-, two- and four-circuit connections are shown in Figs. 285, 286, 287. For the sake of simplicity, the starting winding is omitted in these, but the connection is like the running winding connection. This makes possible the use of more than one voltage on the motor. In the single-circuit connection all poles in each winding are connected in series, for use on maximum voltage, say 220 volts. If half the poles are joined in one series group, and the other half in a second series group, the two groups can then be paralleled across the line. Only half-maximum voltage (say 110) is then used, but since there are two paths, the current drawn from the line is doubled, giving the same power effect.



4 POLE, 4 CIRCUIT CONNECTION FOR ¼ MAXIMUM VOLTAGE

FIG. 287

At the outset it was suggested that the field windings on one type of split-phase motor are placed on the stator by some manufacturers, and on the rotor by others. In the former case the rotor consists of a laminated steel core, mounted on a shaft, and with slots or holes to receive the bars that form the squirrel-cage winding. See Fig. 288. In the latter type of motor, the squirrel-cage winding is placed in the stator slots. In either case the action is the same, but the latter type of motor requires two slip rings to convey the line current to the rotating field windings. The squirrel-cage rotor winding (see Fig. 288) for either type is like that discussed for the shaded pole motor.

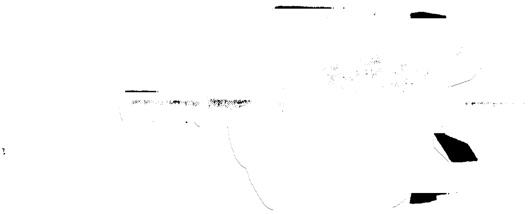


Fig. 288

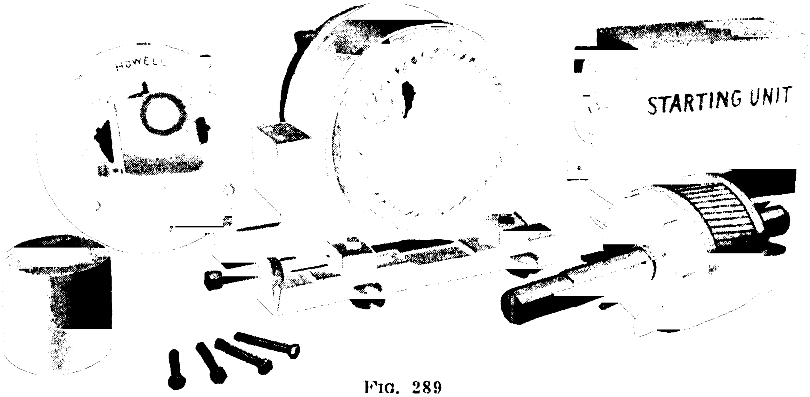


Fig. 289

The split-phase motor is ordinarily made in fractional horsepower sizes. It is used a great deal for such jobs as running small pumps, grinders, fans, domestic-size washing machines.

57. THE CONDENSER TYPE SINGLE-PHASE MOTOR:

This type of single-phase induction motor employs the split-phase principle on a squirrel-cage motor which does not differ

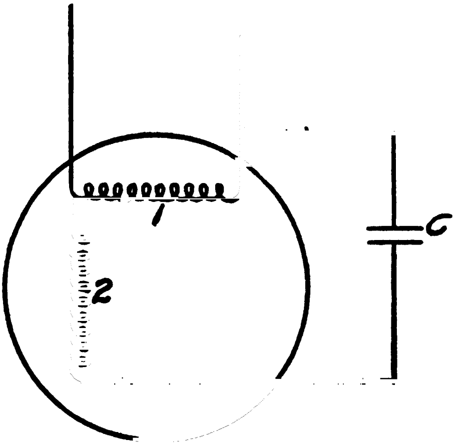


FIG. 290

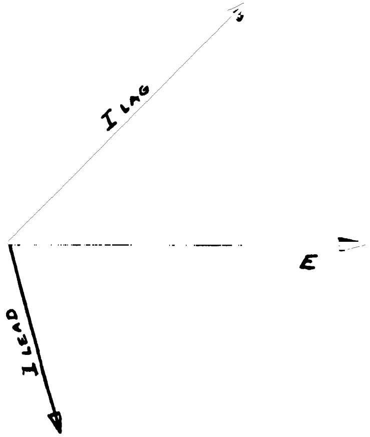


FIG. 291

essentially from a polyphase induction motor. Fig. 289 shows the parts of a Howell single-phase condenser motor.

Observe that the rotor is of squirrel-cage construction, and the stator has coil windings. There are two of these displaced by 90°, as shown in Fig. 290. The second winding has inserted in its circuit a condenser whose purpose is to cause leading current to flow through the second winding. At the moment of starting, the currents in the two windings are

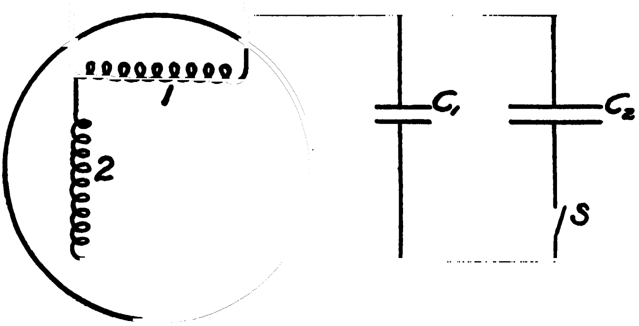


Fig. 292

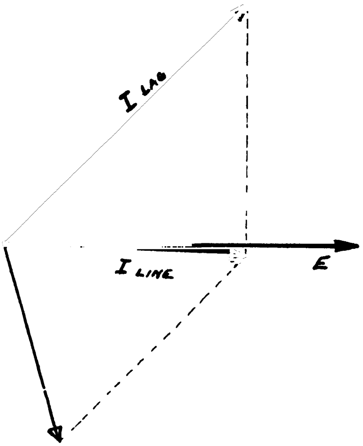


Fig. 293

nearly 90° out of step, as shown in Fig. 291, the current in the first winding being a lagging current. The rotor is enabled to turn over due to the split-phase action of the starting-unit or condenser.

A second condenser may be employed which remains in continuous use while the motor is running. See Fig. 292. The purpose of this condenser is to continue a leading current in the second winding, making out of the motor virtually a two-phase motor. See Fig. 293. The line current at full load is practically in phase with the voltage and the power factor is practically 100%. If the second condenser is not desired, the starting-unit alone may be used. This latter condenser is disconnected after the starting period by a relay. The connections for relay and motor and for reversal of rotation are shown in Fig. 294.

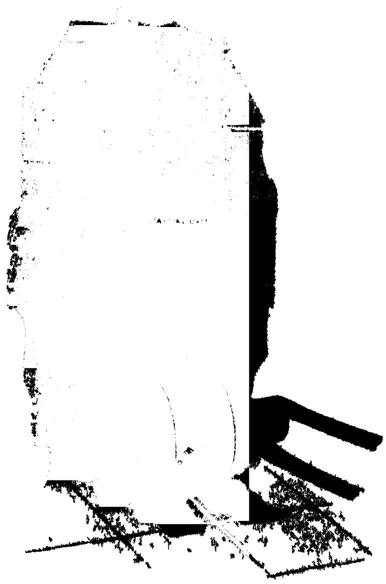


FIG. 294

58. THE REPULSION MOTOR:

The stator of the shaded pole motor was seen to be a combination of a modified direct current field frame (salient poles) and an alternating current rotor (squirrel cage). The repulsion type single-phase motor combines the armature of the direct current machine (Fig. 295) with the stator of the split-phase motor but having only a running winding. See Fig. 296. Merely taking the armature and placing it in the stator is, however, not enough. New connections and certain

FIG 295

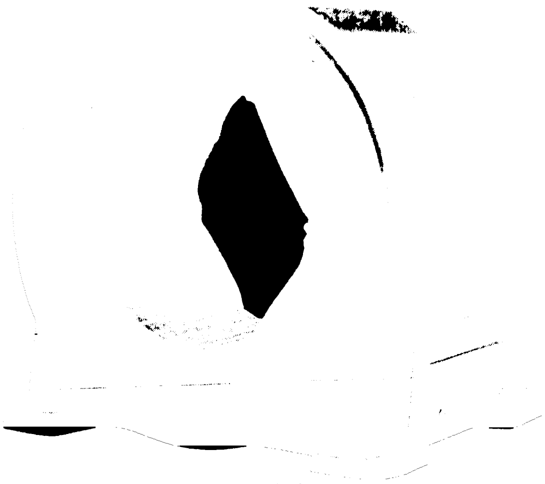


FIG. 296

additions are, of course, necessary, but the result is a machine having characteristics distinctly its own. To distinguish it from other motors, it is called the repulsion motor. Fig. 297 shows a motor of the repulsion type. In the repulsion motor, current is fed from the line into the stator winding, but not to the rotor. As in the case of the shaded pole and the split-phase motor, current is induced in the rotor winding, which consists of coils connected to commutator bars like a wave-wound direct current armature winding.

FIG 297

Brushes, known as short-circuiting brushes, are placed on the commutator. These close the armature circuit and so permit the induced E.M.F. to cause current flow. In view of the fact that the armature is wave-wound, only two brushes are necessary, regardless of the number of poles on the stator. A heavy copper wire connects the brushes together, hence the term "short-circuiting brushes." The brushes actually short-circuit the armature paths of the rotor winding.

The proper location of these brushes is of great importance, and the brush location, of course, depends on the manner in which the armature leads are brought out to the commutator bars. Standard practice would place the brushes in one of two possible positions, either near the center of the pole pieces or near the midway position between adjacent poles. See Fig. 298. When the top leads of the coils are brought out straight from the slots to the commutator, the

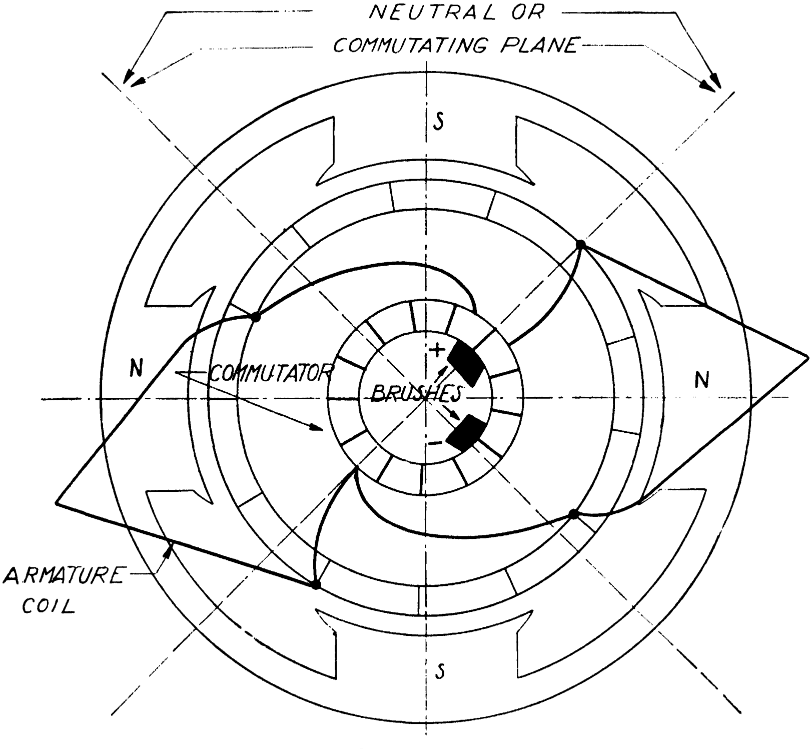


FIG. 298

brushes are near the center of the poles. When the top leads are brought out 90° E. away from the coil or toward the center of the coils, the brushes are placed near the midway position between adjacent poles. See Fig. 299.

For the sake of convenience let us take a two-pole motor having a rotor, with the top leads of the winding brought out straight to the commutator segments. Also let us pay particular attention to the results obtained by placing the brushes in various positions on the commutator. Fig. 300 is a drawing of a rotor winding showing all of the coils and the connection of the leads. This same rotor with its winding is

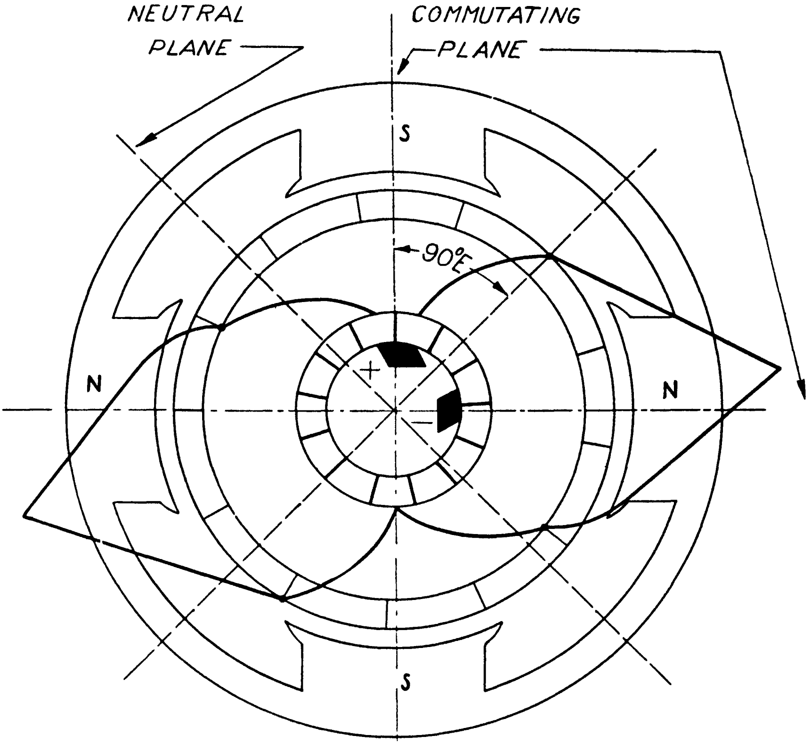


Fig. 299

reproduced in symbolic form in Fig. 301. The latter picture is more easily studied and current flow is more easily traced. The top lead of the coil is represented by the full line and the bottom lead is indicated by the dotted line. The commutator connection is the same. Assume for this rotor winding that the brushes are placed on the line that passes midway between the poles. The current passing through the stator winding sets up lines of force which pass from the stator steel to the rotor steel, cutting the winding conductors on the rotor and hence generating an E.M.F. The latter causes current flow through the rotor winding. Hence we should expect the rotor to begin turning over, but we find this does not happen. Why?

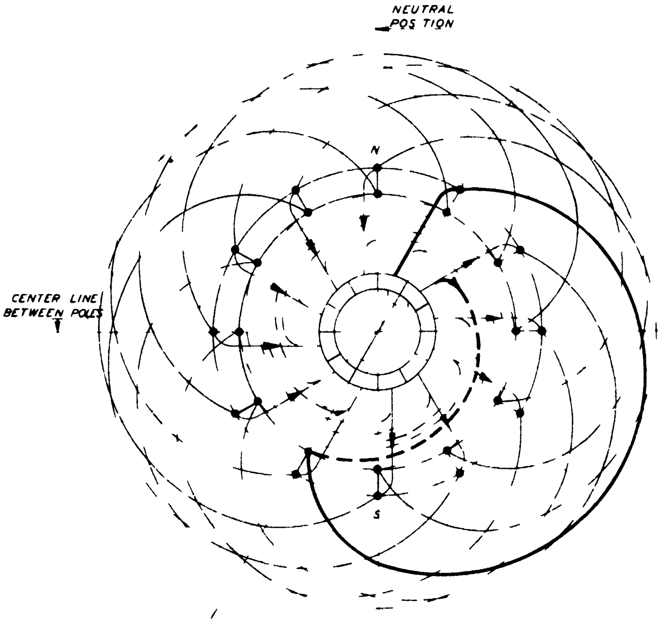


FIG 300

Observe, first of all, that because the rotor is at rest, the E.M.F. induced in the rotor winding is a voltage that is generated by transformer action. The stator winding acts as the primary coil, the rotor winding acts as the secondary coil of a transformer. Moreover, with the brushes set as they are, the rotor winding is divided into paths, the upper half of coils and the lower half. And note also that in the upper half the coils on the left generate voltage which would tend to push current in a clockwise manner through the path, whereas the coils on the right in the upper half generate voltage oppositely. Similarly there is voltage opposition in the lower path. The net result is zero voltage in each path. Hence no current flows in the rotor winding and so there is no

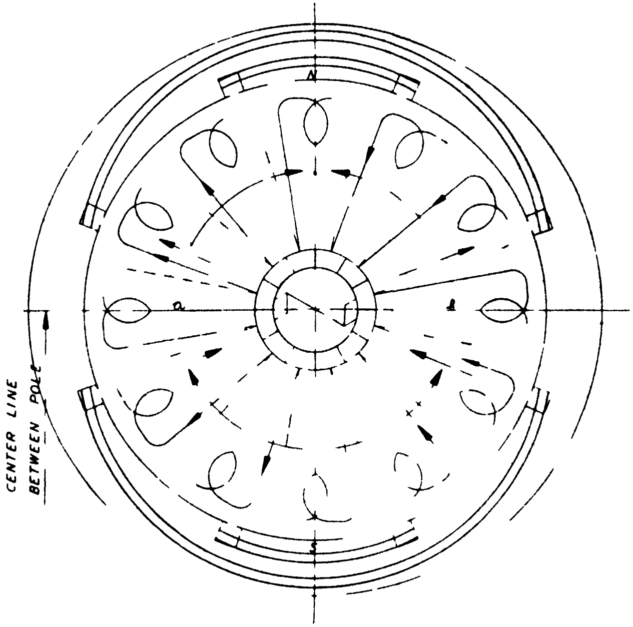


Fig 301

tendency for the rotor to begin turning over. Coils *a* and *b* are short-circuited by the brushes and therefore they contribute no current. If a current could flow, this current would set up poles in the rotor iron near coils *a* and *b*. The reaction between these poles and the stator poles would make possible the torque necessary for producing rotation. In fact this would be the very best position for the brushes from the standpoint of torque produced. But since no current flows, we get no rotation when the brushes are in their present position.

Suppose now we shift the brushes so that they are under the middle of the pole pieces as shown in Fig. 302. Again the brushes divide the winding into two paths. The coils on the left half of the rotor constitute one path, those on the right constitute the second path. The E.M.F. induced at standstill, when current flows through the stator winding, is induced by transformer action, and in the path on the left is clockwise, while in the path on the right it is counter-clockwise. Now this is ideal for current flow. And since the brushes short-circuit these paths, current actually does flow. Again we should expect rotation to occur, but again the rotor fails to turn over. This time, because there is no torque produced.

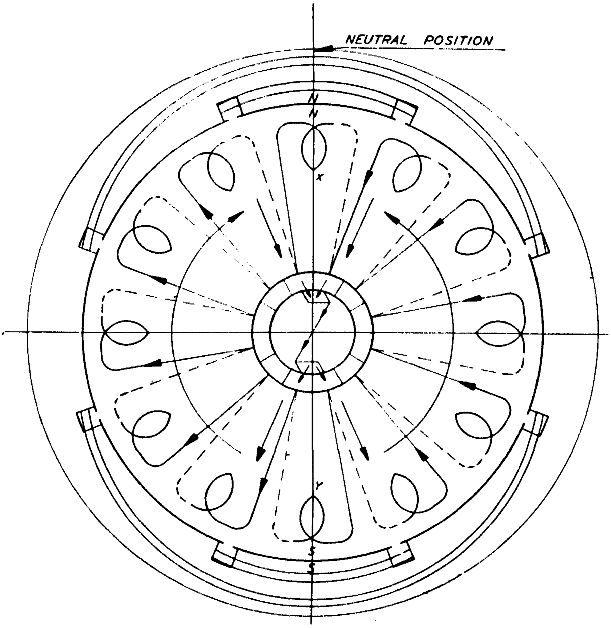


FIG. 302

Observe in Fig. 302 that the stator poles are located at the top and at the bottom of the stator. Observe also that the current in the rotor, although it is the maximum possible for any position of the brushes, sets up poles in the rotor core, and at the top and at the bottom, directly opposite the stator poles and in line with the center of the shaft. Now the reaction between these poles results in a thrust of the rotor against the bearing surfaces. Again there is no rotation, and although the poles have maximum strength, there is no leverage. In other words, the north pole of the rotor is directly under the north pole of the stator, and the south pole of the rotor is directly under the south pole of the stator. Like poles repel each other, but no matter how great the repelling effect may be, the result is a force directed toward the center of the shaft. Hence the rotor cannot move.

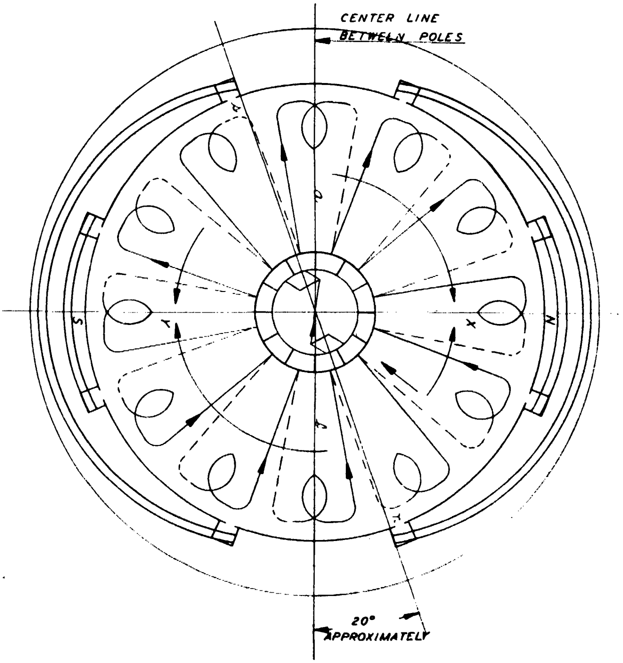


FIG. 303

Now let us shift the brushes to a position slightly away from the line that passes midway between the poles of the stator as in Fig. 303. The induced E.M.F. and current in the upper path coils are clockwise for the coils on the left, and counter-clockwise for the coils on the right. But now note that the E.M.F.'s on the two sides of this upper path, though opposite, are not equal, since there are more coils on the left than on the right. The net voltage, therefore, causes a current to flow in the coils of the upper half of the rotor in a clockwise sense. Of course, this net voltage is not the maximum voltage possible, therefore the current in the coils is not the maximum possible either. Similar conditions exist in the coils of the lower path of the rotor. The resultant voltages in the upper and lower paths of the rotor windings are in the same direction through the brushes, hence current flows in the same sense to the brushes. However, the current is small and

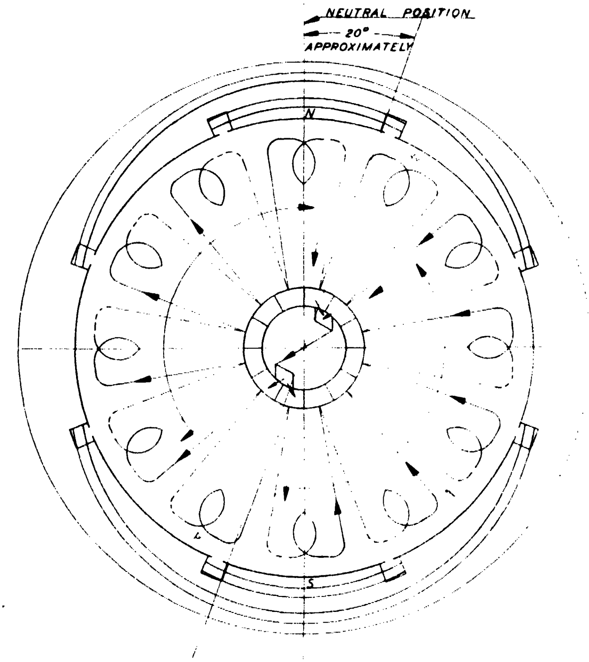


FIG. 304

so it sets up weak magnetic poles in the rotor. These poles are now located to one side of the stator poles. Hence the reaction between stator poles and rotor poles now results in a push not in line with the shaft. This force now has leverage; it results in a turning effect on the rotor, and the latter begins to turn over. But the torque or turning effect is weak, since the rotor current and poles are weak. And this relative weakness exists because some coils work in opposition to others in each path.

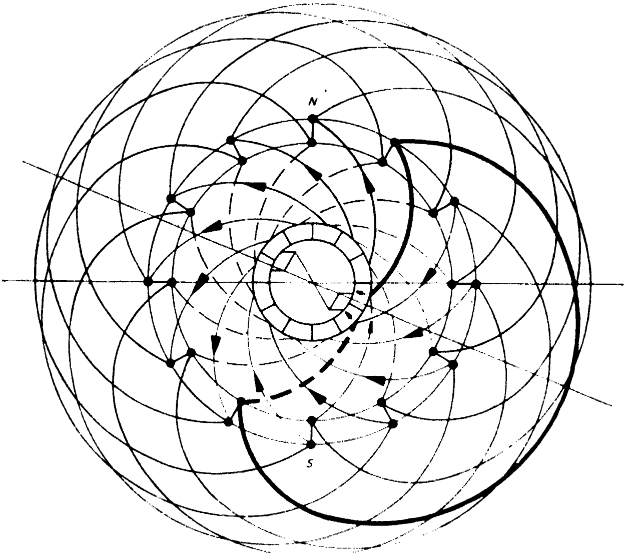


FIG. 305

We can reduce this opposition within each path to a minimum by shifting the brushes to a position about 20° E. from the line passing through the center of the stator poles as shown in Fig. 304. This illustration shows that now the sense of the E.M.F. in the coils on the left side path of the rotor is upward. The direction of the E.M.F. in the coils on the right side of the rotor is also upward. Both tend to push current toward the brushes in the same sense. With this position of the brushes, the coils in each path tend to work together, thus producing a higher current, which means stronger rotor poles, and therefore more torque or turning effort.

It will be remembered that when the brushes were in the neutral position (center of pole faces) the rotor was unable to turn over. Shifting the brushes to one side of the neutral position in a clockwise sense produced clockwise rotation. If the brushes are shifted to the other side of the neutral position, or in a counter-clockwise sense, the rotor will turn in a counter-clockwise direction. Hence the method for reversing the direction of rotation of a repulsion motor is to shift brushes from one side to the other side of the neutral position.

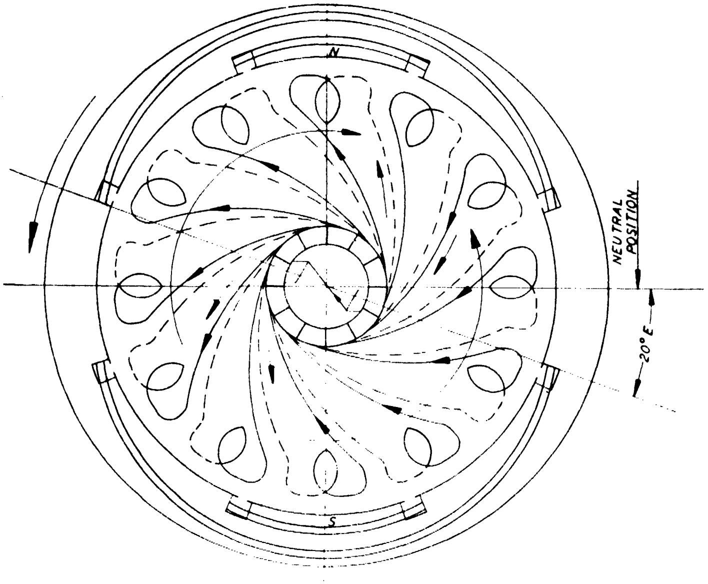


Fig. 306

It was stated previously that two positions for the brushes were possible, depending on how the lead connections are made to the commutator. So far the whole discussion has concerned a rotor winding whose top leads are brought straight out to the commutator. When the top leads are brought out to commutator segments 90° E. away from the coil slots, the neutral position is 90° E. away from the middle of the stator poles, or in other words, the neutral position is midway between the poles. The brushes are again placed about 20° E. away from the neutral position. Fig. 305 shows a complete rotor winding with leads brought out with a 90° E. "throw" to commutator bars. It also shows the new neutral position and the correct brush position. Fig. 306 shows the same winding as in Fig. 305 but symbols are used to represent the coils.

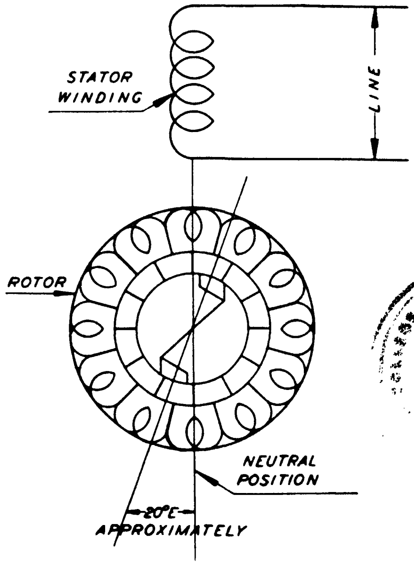


FIG. 307

By arranging the brush rigging to permit easy shifting of the brushes from the center of a pole to the end of the pole face, the repulsion motor can easily be made into a variable speed motor. Such a motor can be adapted for operating hand-fed printing presses.

Another method for varying the speed of the repulsion motor is to use an externally connected transformer for varying the voltage. Any change in voltage will produce a corresponding change in speed.

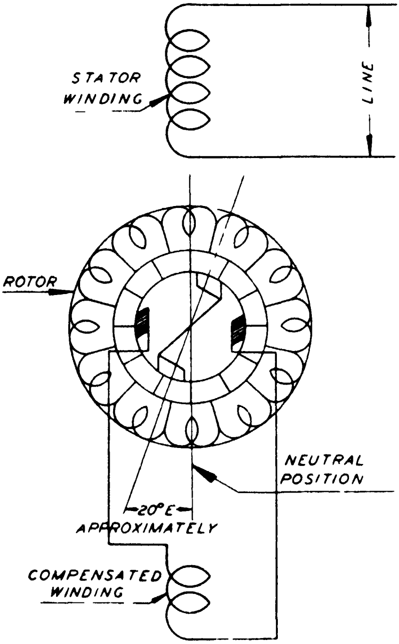


FIG. 308

59. MODIFICATIONS OF THE STRAIGHT REPULSION MOTOR:

The repulsion motor can be modified by adding one or more windings. It is possible to produce many different kinds of motors, each having slightly different characteristics. Fig. 307 shows a schematic diagram of a straight repulsion motor. Fig. 308 shows one way of modifying the repulsion motor. A winding known as a "compensating" winding has been added. This winding is placed on the stator with the running winding. It may be placed in the same slots with the coils of the running winding, or it may be placed in separate slots provided for it. Whichever method is used there are as many poles in the compensating winding as in the main field winding. The current that energizes the compensating winding is drawn from the rotor through an extra set of brushes placed about 90° E. away from the neutral position of the short circuiting brushes.

In the discussion on the location of the short-circuiting brushes, it was noted, that when the brushes were placed on the line passing midway between poles, there was no current flowing. It is reasonable for the student to assume that no current flows through the compensating brushes if they are placed midway between the poles of the stator. When we were considering the brush location for the short-circuiting brushes, we were interested in getting the rotor to turn over. At standstill, the induced current is set up by transformer action only. It is reasonable to assume that very little current is present in the compensating winding during the starting-period. But as soon as the rotor has begun to rotate, there exists also a speed E.M.F. in each winding, because the rotating coils now cut lines of force. Hence current does flow in the compensating winding even though the brushes are located 90° E. away from the neutral position.

The ordinary or straight repulsion motor operates at a low power factor. By adding a compensating winding the power factor is raised for all loads of the motor, even giving a leading power at no load, but the efficiency may at the same time be lowered. While one manufacturer builds a motor having connections as shown in Fig. 308, other manufacturers use different schemes of connection. To show all of these methods is not desirable, because it would tend to confuse the student. Regardless of the manner of connecting the compensating coil, its function is in general the same. Such a motor is known as the compensated repulsion motor.

Another modification of the straight repulsion motor is to place two windings on the rotor instead of on the stator.

These windings have no electrical connection. A squirrel-cage winding is added to the regular rotor winding. Fig. 309 is a schematic diagram of such a motor. The squirrel-cage winding is placed below the coil winding, but in the same slots.

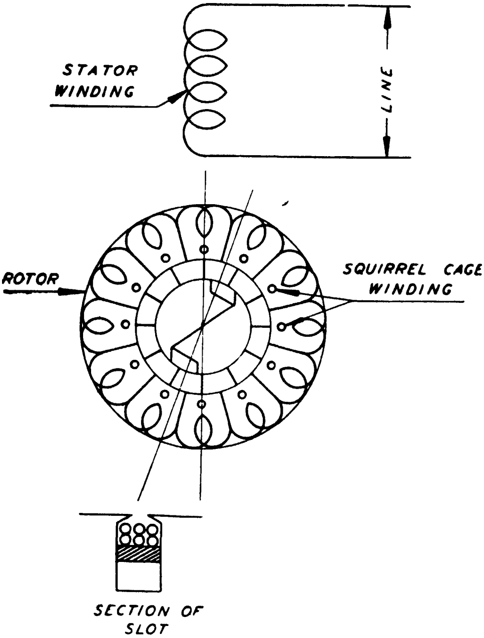


FIG. 309

The two windings are separated by an iron or steel barrier. The barrier may be part of the core by having the slot for the squirrel-cage winding punched below the slot for the coil winding. Or a deep slot may be used, placing the squirrel-cage on the bottom of the slot, then placing an iron or steel spacer on the top of the squirrel-cage winding. The rotor coils are then placed in the slot above the iron barrier.

A motor having both windings uses the repulsion method for starting. In addition to certain repulsion motor characteristics, this machine takes on some of the characteristics of the induction motor. Hence it is known as a repulsion-induction motor.

A further modification consists in adding a compensating winding, as shown in Fig. 310. The introduction of the compensating winding improves the power factor and operating characteristics of the machine. This is a popular type of motor but again we find various methods employed in connecting the compensating winding.

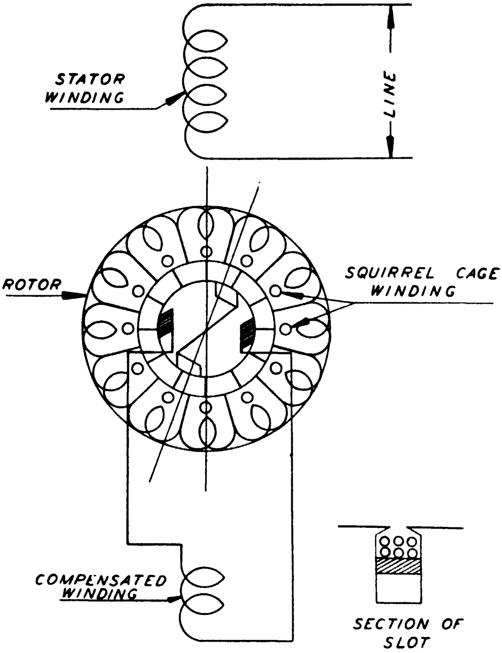


FIG. 310

Another very popular type of repulsion-induction motor, is the repulsion-starting induction-running motor. From the standpoint of mechanical construction it differs somewhat from the repulsion-induction motors so far considered. It has a single winding on the stator and a single winding on the rotor as in the straight repulsion motor. See Fig. 311. The rotor of one type of motor is equipped with a mechanical device for removing the brushes and short-circuiting the commutator bars. Hence the motor starts as a repulsion motor and after the rotor comes up to speed the rotor coils are automatically short-circuited and the winding then becomes equivalent to a squirrel-cage winding. A governor controlled by centrifugal force acts against the tension of a spiral spring. When the rotor approaches full speed, centrifugal force acting on the governor overcomes the force of the spring, causing a drum or sleeve to move forward which in turn forces the brushes away from the flat face of the commutator and at the same time allows a group of small copper segments that are tied together (called a "necklace") to make contact with the commutator bars on the inside of the commutator, thus short-circuiting bars and coils. When the motor is stopped, the force of the spiral spring brings the brushes back to the commutator and also removes the short-circuiting device. Hence the motor starts as a repulsion motor and when up to speed runs as an induction motor. Since it starts as a repulsion motor the method for reversing rotation is the same as for the straight repulsion motor.

FIG. 311

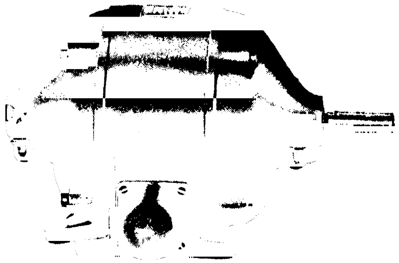


FIG. 312

Another motor of this kind has the rotor equipped with a mechanical device, also operating by centrifugal force, to short-circuit the commutator segments, but without removing the brushes from the commutator. Not all of the commutator segments are short-circuited. Certain segments are short-circuited to produce in effect a squirrel-cage winding of a somewhat higher impedance. The brushes remain on the commutator at all times. See Fig. 312.

Practically all repulsion and repulsion-induction motors have the stator winding leads brought out through the frame in such a way as to permit connections for two voltages. By connecting the leads of the stator in what is known as the series connection (Fig. 313), the motor is connected for maximum voltage. Connecting the leads in the parallel connection as shown in Fig. 314, the motor is connected for operation on one-half the maximum voltage. This permits operation of the motor at full rating on either of two voltages, because at the lower voltage the parallel connection allows double current capacity—hence full power rating.

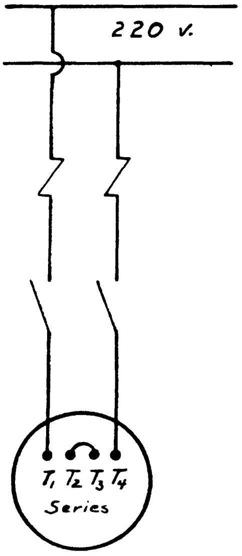


FIG. 313

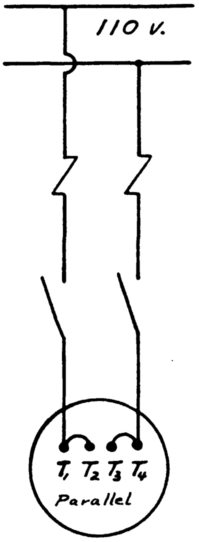


FIG. 314

60. THE SERIES MOTOR:

Direct current motors do not adapt themselves for use on A.C. circuits. It is true that the series motor will run on A.C., but, unless considerable change is made in the design and construction, results are not satisfactory. We have therefore the series motor designed for D.C. circuits; the series motor designed for A.C. circuits; and the universal (series) motor which operates on either D.C. or A.C.

An ordinary D.C. motor connected to an A.C. source shows an undue rise in temperature and excessive arcing at the brushes. The heating effect is due very largely to the eddy currents and hysteresis in the solid cores of the field poles. The field poles and yokes of the A.C. series motor are laminated, and iron with high-grade magnetic qualities is used in order to prevent much of this heating effect. The D.C. series field would have too high a reactance, hence very few turns per pole are put into the field coils of the A.C. motor. The high reactance would limit the field current too much. Also in order to prevent too weak a field, the poles are given a larger area. They are short and stubby. Then, too, the air gap is reduced to a minimum in order to reduce the reluctance of the magnetic path.

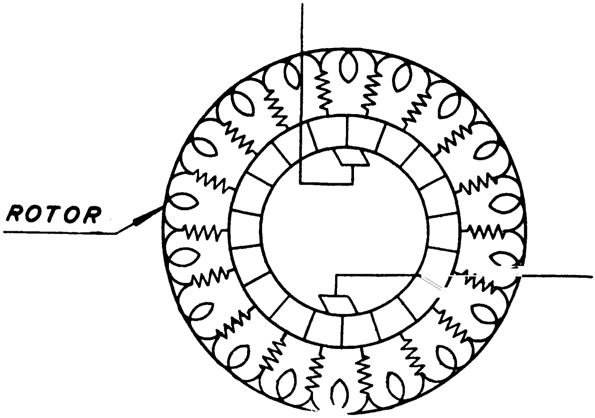


FIG. 315

The other serious difficulty, "sparking" at the commutator, is due to the fact that the coil undergoing commutation has induced in it an E.M.F. due to transformer action. The field is an A.C. field, hence even though the ordinary speed E.M.F. may be at a minimum, the alternating flux that threads the short-circuited coil causes heavy current flow and therefore sparking. This is offset in part by putting very few turns into the coils and having many more coils, and hence many more commutator bars. But in larger machines even this is not sufficient to reduce sparking to a minimum. Specially designed resistance leads from each coil to the commutator bar are introduced in order to cut down the current in the short-circuited coil. See Fig. 315.

Still another variation in design from the standard D.C. series motor is the manner of compensating for armature reaction. D.C. motors are supplied with interpoles whose function is to offset the magnetizing action of the armature current and its distorting influence on the main field. In the A.C. series motor, armature reaction is decidedly worse than in the D.C. motor because the latter has a strong field, the former a relatively weak field. Hence in the larger A.C. series motors a second winding is put on the stator. This winding is embedded in slots in the pole faces. It is called a compensating winding. Its function is similar to the function of an interpole, namely, to offset armature reaction. Fig. 316 shows by symbolic diagram the internal connections for a

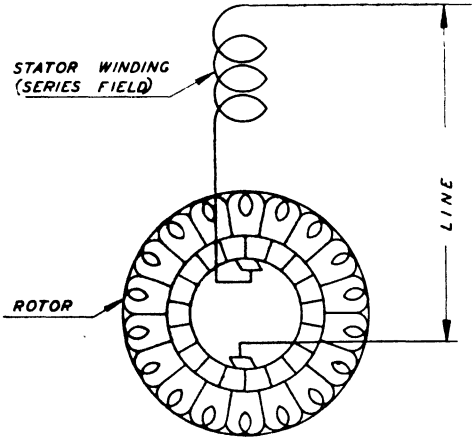


FIG. 316

series motor without compensating winding or resistance leads. Fig. 317 shows the compensating winding without resistance leads.

The "universal" motor is a series motor designed to operate on either A.C. or D.C. circuits. It is usually of fractional horsepower capacity, and hence aside from laminations being used throughout its entire magnetic path, it has little other variation from the standard D.C. type. It therefore lacks good efficiency and may show tendency toward sparking, but in general the loads on it are so light as to make careful design neither advisable nor necessary.

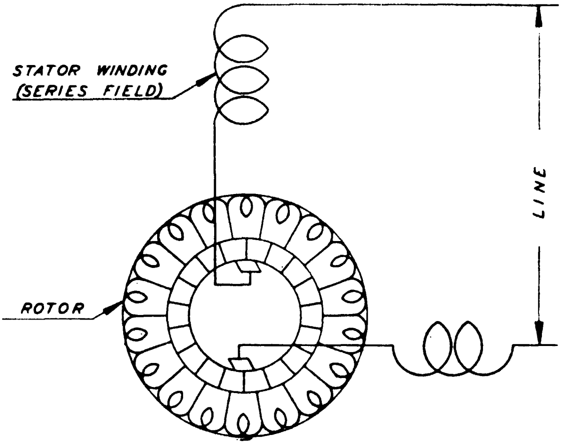


FIG. 317

61. SYNCHRONOUS SPEED, SLIP:

In chapter II we had occasion to use the equation

$$f = \frac{\text{R.P.M.} \times P}{60}$$

in which f is the frequency, R.P.M. the revolutions per minute, P the number of pairs of poles, and 60 represents the number of seconds per minute. This equation enables us to determine the frequency of the voltage generated by an alternator when the speed and number of poles are known. Now if we impress a voltage on the stator winding of a motor and rotation of the rotor results, the speed at which the rotor rotates is determined in part by the number of poles in the stator and in part by the frequency of the voltage impressed. The equation above applies equally well in the case of a motor. Of course, it is desirable to re-write the equation, solving for the speed or R.P.M. Thus,

$$\text{R.P.M.} = \frac{f \times 60}{P}$$

Then for a two-pole machine connected to a 60-cycle voltage, we should expect to get

$$\text{R.P.M.} = \frac{60 \times 60}{1} = 3600$$

3,600 revolutions per minute. Similarly for a four-pole machine the speed is

$$\text{R.P.M.} = \frac{60 \times 60}{2} = 1800$$

And for a six-pole machine the speed would be 1,200 R.P.M. This speed as based on the above equation is called the synchronous speed of the motor. Motors do not ordinarily deliver exact synchronous speed, even at zero load. Thus a four-pole single-phase motor running without load might give 1,790 R.P.M. instead of 1,800. If there were no power losses inside the motor we could expect 1,800 R.P.M. On load, the speed of this four-pole motor actually drops to perhaps 1,750 R.P.M. The full-load speed recorded on the name-plate might actually be 1,750 R.P.M. The difference between the actual running speed and the "ideal" or synchronous speed is in this case 50 R.P.M. This difference is called the rotor "slip." Usually slip is expressed in R.P.M. or as a % of the synchronous speed. Thus, the slip of 50 R.P.M. suggested above, expressed in %, is

$$\text{slip (in \%)} = \frac{1200 - 1150}{1200} = \frac{50}{1200} = 4.2\%$$

Slip is a very important feature about A.C. motors.

62. TORQUE:

We have had occasion to use this term several times and the student should understand its significance. Torque means turning effort or turning effect of a force which is applied on an object at some distance from the axis about which rotation is to take place. If I lift a bicycle wheel off the ground, I use a force. But this force does not cause the bicycle wheel to rotate. If I wish the bicycle wheel to rotate about its axis, I again use a force, but preferably I apply the force to the rim of the wheel. This is done to give leverage to the force. Without leverage, a force can move an object, but it cannot cause the object to rotate. Torque is the result of force and leverage together. Hence it is calculated by

$$\text{Torque} = \text{Force} \times \text{arm}$$
$$T = F \times l.$$

After all, a motor is used to turn over machinery of some kind. Its turning effort or torque is therefore very important, not only while the motor is carrying its normal load, but it is of importance in getting the load started. The "starting torque" of a motor is a prime consideration in deciding the fitness of a motor to do a certain job. Then, too, it is desirable to know what the "pull-out" torque may be. That is, load may be added to a motor, with resulting dropping off of speed. How long will this continue? There is usually a very definite load which if placed on a motor results in a breakdown of speed to zero, the motor simply refusing to carry this load and coming to a standstill. This torque is called the "pull-out" torque of the motor.

63. EFFICIENCY:

A simple definition of efficiency is to be found in the equation

$$\text{Efficiency} = \frac{\text{output}}{\text{input}}.$$

If we determine the input into a motor and the losses, the difference between these two represents the output. The ratio of the output to the input in terms of % is the efficiency. Efficiency is the answer to the question: What portion (%) of the power put in comes out?

The efficiency of a motor is not the same for all load conditions. Usually it is best near full load, and poorest at very light loads or no loads.

64. SINGLE-PHASE MOTOR CHARACTERISTICS:

The performance of the different types of single phase motors under different conditions of load is particularly interesting to the man who must specify the type of motor to be purchased for a given job. Sometimes a competent engineer is available, but often it is the duty of the chief electrician, or perhaps the purchasing agent has to do the job. Sales engineers are available for consultation. But in general, the intelligent electrical man should know what a given motor will do. He should know what the behaviour of a given motor will be as to speed, power factor, torque, efficiency, under varying conditions of load. Let us consider these briefly for each type of single-phase motor.

a) Single-phase induction motor (split-phase): This motor is common only in the fractional horsepower sizes and is used for driving washing machines, sewing machines, mangles, small ventilating fans, grinders, churns, separators, and small lathes. The starting torque is usually not more than 150% of the full-load running torque. Hence it is not well adapted for heavy starting loads. The Wagner type BB motor (Fig. 318) is a split-phase induction motor of this type, but with well-balanced characteristics. Fig. 319 shows the characteristics of the Wagner type RB split-phase motor.

The split-phase motor operates at fairly low power factor and often at efficiencies not above 70%. Its speed is fairly constant. It is not much used in the sizes above 1 horsepower.

b) Repulsion motor:

The power factor of the straight repulsion motor is low except near synchronous speeds. But with a compensating winding the power factor improves, so that unity power factor or even leading power factor may be attained at speeds above synchronous speeds. This

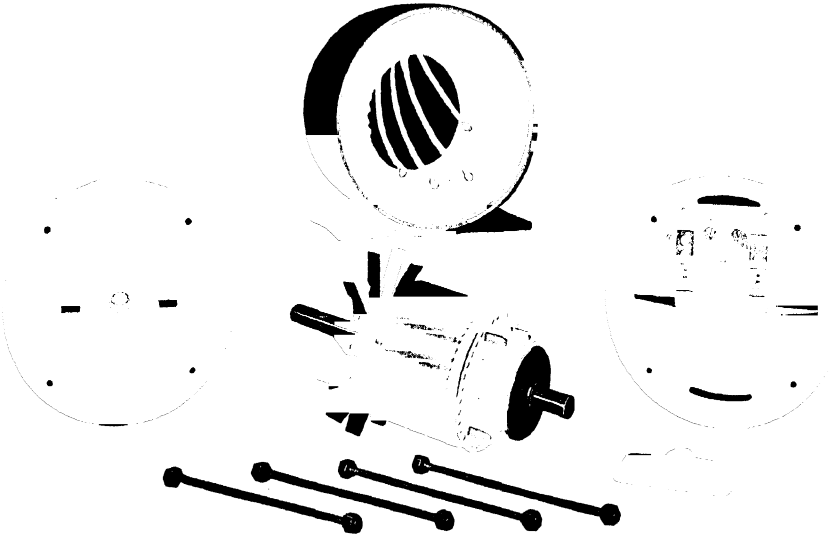


FIG. 318

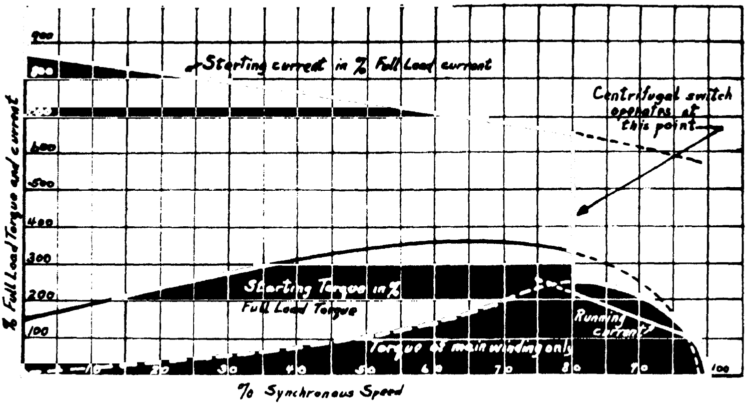


FIG. 319

motor has a high starting torque and is therefore applicable where heavy starting duty is demanded as for traction purposes on railways. Its speed characteristic

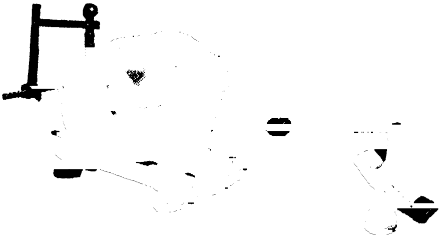


FIG. 320

is similar to that of the D.C. series motor. By far the most important application of the repulsion motor is in combination with the induction type to produce the repulsion-induction motor.

FIG. 321

An important application of the straight repulsion motor is in connection with printing presses. By shifting the brushes variable speeds are obtained to suit the convenience of the press-feeder. The motor shown in Fig. 320 is of the repulsion type, made by the Kimble Electric Company. The speed is varied by foot or hand control. Speed reduction is accompanied by a corresponding cut in power consumption.

c) Repulsion-induction motor:

The repulsion principle used for starting gives this motor an excellent starting torque, comparable to that of the series motor. Its starting torque may be 300% of the full-load running torque. It combines with this the constancy of speed shown by the induction motor. It is well adapted for use on compressors, pumps, blowers, and similar types of loads.

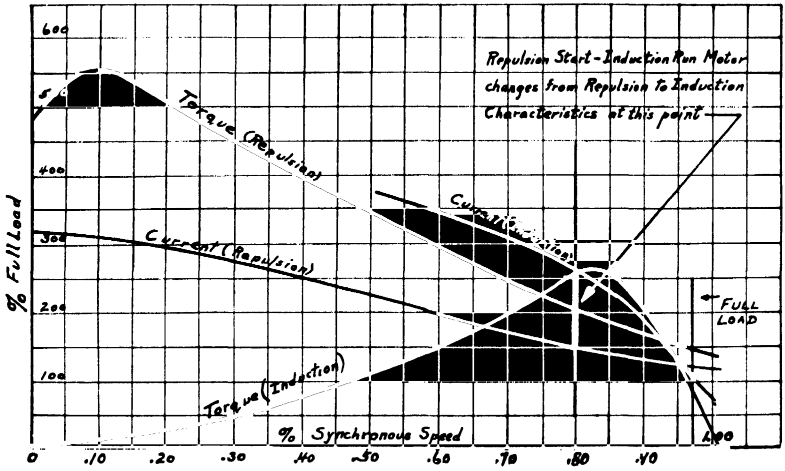


FIG. 322

The power factor of this motor is greatly improved by the compensating winding, so that good power factor conditions are maintained for almost all loads. The efficiency is apt to be low without compensating winding, but with the latter, an efficiency of 80% or more can be attained over a wide range of loads. At light loads the efficiency is, of course, very poor. Fig. 321

shows the Wagner type BA repulsion-induction motor and Fig. 322 shows its characteristics. Another repulsion-induction motor is the type SCR made by General Electric Company (Fig. 323). This motor also has a squirrel-cage winding on the rotor, but no short-circuiting device for the coil winding. Its characteristics are shown in Fig. 324.

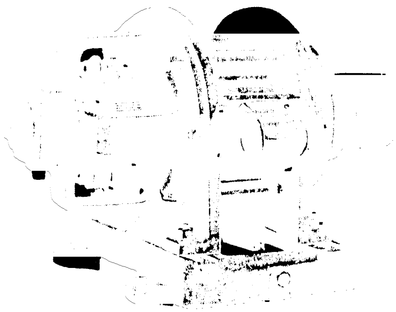


FIG. 323

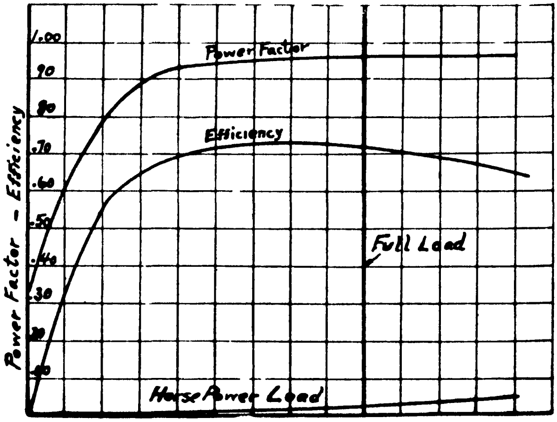


FIG. 324

d) Series motor:

The A.C. series motor has characteristics like those of the D.C. series motor. Its speed varies over a wide range with varying load. It develops high starting torque. It operates at fairly good efficiency over a wide range of load and its power factor is fairly high.

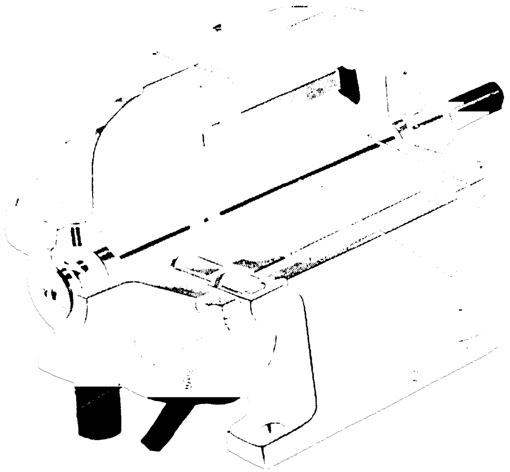


FIG. 325

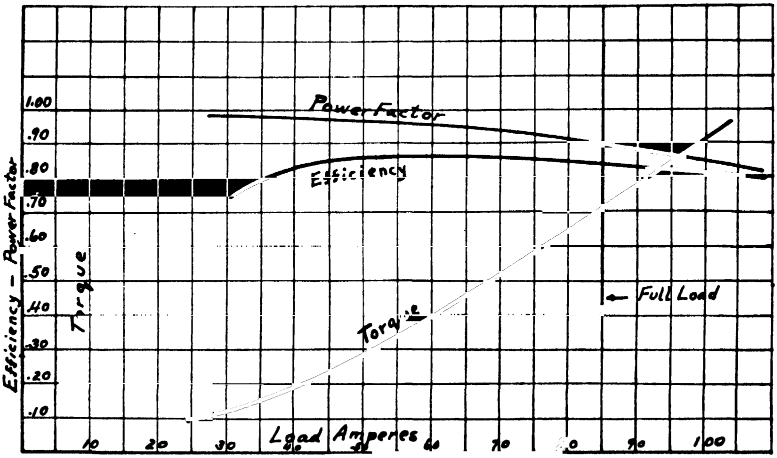


FIG. 326

Due to commutation difficulties the voltage is kept much lower than with D.C. series motors. The latter take current at 600 volts for railway work. A.C. series motors are usually restricted to 250 volts and 25 cycles or less.

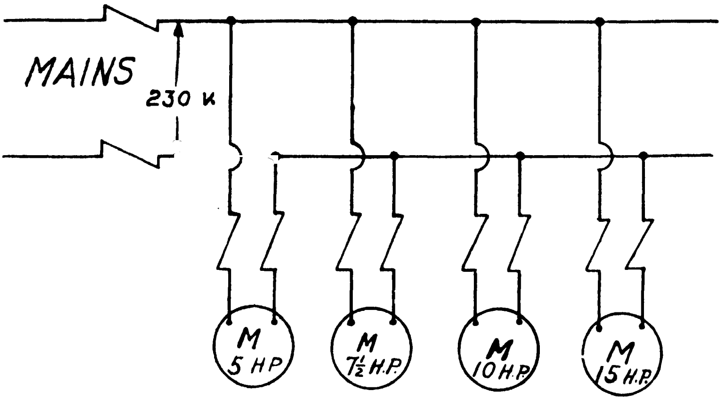
Small series motors are well adapted for use with electric drills, motion picture machines, advertising devices, small portable tools, etc. The Westinghouse type ADS series motor is shown in Fig. 325. It may also be used on D.C. but for low speeds a series resistance is required. The characteristics of an A.C. series motor are shown in Fig. 326.

PROBLEMS—CHAPTER VI

1. What size single-phase motors are permitted on the lighting lines in your community?
2. What is the largest size single-phase motor permitted on a single-phase power line?
3. Is it permissible to use a single-phase motor on a three-phase power line in your community? If so, what is the largest size single-phase motor permitted?
4. Refer to Tables in the Appendix. Obtain from these tables the following data:
   - *a*) Starting and running fuse capacities for a 2 H.P. split-phase motor (120 volts).
   - *b*) Starting and running fuse capacities for a 5 H.P. split-phase motor (240 volts).
   - *c*) Starting and running fuse capacities for a 10 H.P. repulsion-induction motor (240 volts).
   - *d*) Starting and running fuse capacities for a 15 H.P. repulsion-induction motor (240 volts).
   - *e*) Size wire needed for each of the motors in this problem.
5. A 5 H.P. motor operates on 220 volts at 80% efficiency and 75% power factor at full load. What is the full-load running current?
6. If the power factor of the motor in problem 5 were raised to 85% what would be the full-load running current?
7. Starting current is roughly considered to be 2½ times as large as the running current. On the basis of the full-load current of the motor in problem 5, what is the probable starting current for

this motor? What size fuses both running and starting should be used? What size line wire should be used?

8. When several motors of different sizes are fed from the same main lines, the size of the wires feeding each individual motor is determined by the 2½ times full load current rule given in problem 7, but the size of the main line feed wires is determined as follows: Multiply the full load current of the largest motor by 2½, and add to this the full load currents of all the other motors. That size wire whose current carrying capacity (see Appendix table for all insulations) is next highest to this total sum is the size wire to be used for the main line, and this total current also determines the size of the main line fuses.



In accordance with the above rule, and with the aid of the tables in the Appendix, determine the size of main line fuses, the size of the main line wires, and the size of the wires leading to each individual motor for the circuit shown in the diagram.

9. Repeat problem 8, assuming that the 10 H.P. motor is changed to 15 H.P.
10. Draw a plan diagram of the stator winding of six-pole split-phase stator. The poles are to be connected in series for operation at 220 volts. The stator has 30 slots. Show both running and starting windings. Show also line connections.
11. Assume that connection in problem 10 result in clockwise rotation. Modify connections so as to reverse rotation.
12. Modify connections of problem 10, for operation of the motor on 110 volts.

13. Draw symbolic diagram of the rotor of a repulsion motor. The rotor has 18 slots, 18 coils, and 18 commutator bars. The leads are brought out straight. Place the brushes correctly and indicate direction of rotation. Show also how reversal of rotation is obtained.
14. Repeat problem 13, assuming the coil leads brought out at a 90° E. "throw."

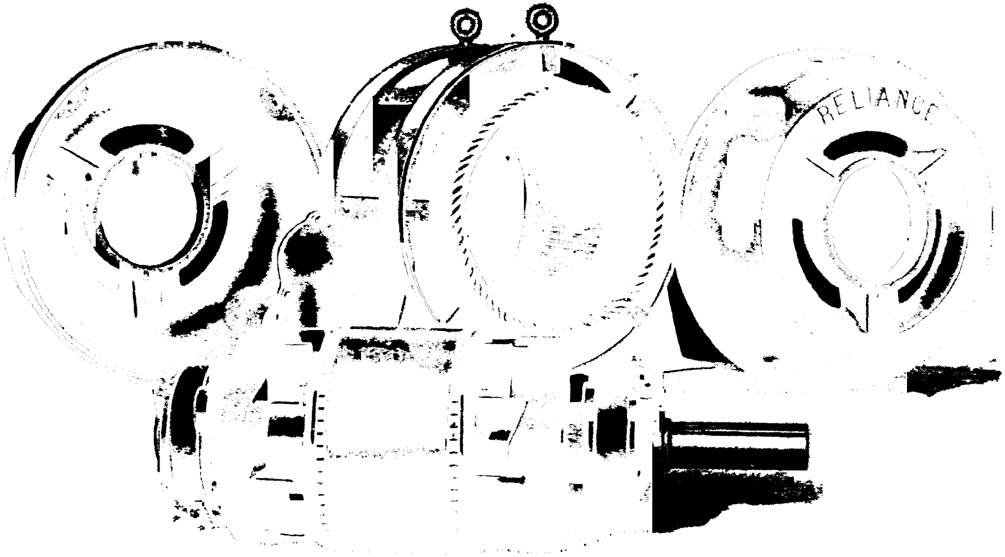


Fig 327

CHAPTER VII

THREE-PHASE MOTORS

65. THREE-PHASE MOTOR STATOR CONSTRUCTION:

Three-phase motors are classified as: the squirrel-cage induction motor, the wound rotor induction motor, and the synchronous motor. These are three distinct types of machines, each with its own characteristics and field of application. In a general way, the differences in the construction of the three motors exist only in the rotor. The frame or stator may be the same for each machine. See Fig. 327.

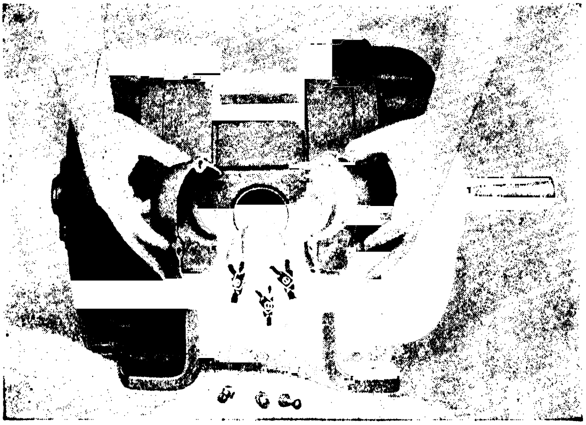


FIG. 328

The frame is made of cast steel, cast iron, or pressed steel, into which is pressed a laminated, silicon steel core called the stator core. The laminations are held together firmly by bolts or rivets. Note the slots equidistant around the inner circumference of the core. See Figs. 328, 329. The stator is wound much like an armature, except that the coils are placed on the inner, instead of the outer surface.

Each coil is made up of a number of turns of insulated (usually double cotton covered) copper magnet wire. See Fig.

330. The cotton covering prevents the turns from coming into contact with each other, but it is not enough to effectually prevent the coils in the slot from grounding with the core; therefore, additional insulation is needed. The slot insulation usually consists of treated paper and varnished linen. To insulate the coils from each other outside of the core, linen tape is used. It extends from slot to slot around the ends of the coils. Another insulation that is important

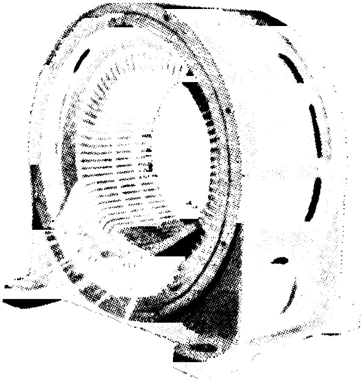


FIG. 329

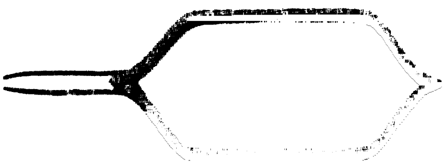


FIG. 330

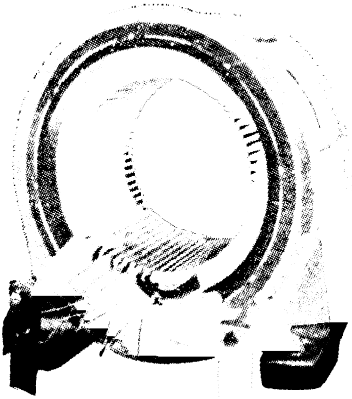


FIG. 331

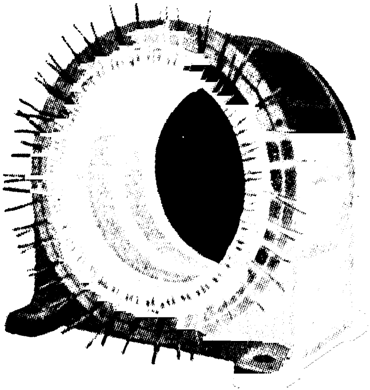


FIG. 332

and must not be overlooked is phase insulation. It consists of heavy varnished cloth or canvas and is placed between coils of different phases on both sides of the frame. See Fig. 331. The phase insulation is trimmed off when the whole winding is in place.

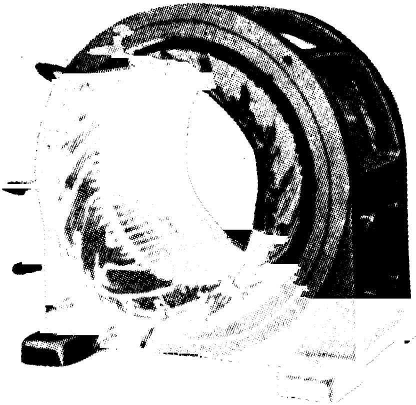


FIG. 333

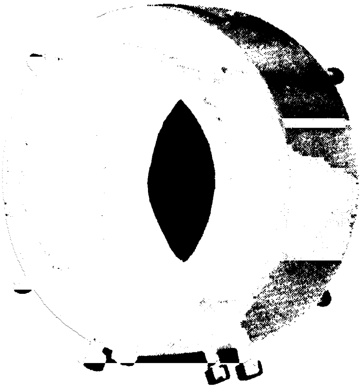


FIG. 334

When the coils are in place (Fig. 332), the leads are connected together for a particular type of motor connection. The first step is to connect those coils together that form a pole and then to connect up the proper poles to form a

FIG. 335

phase. Correct polarity for each pole must be obtained. The illustration may give the impression that it is a difficult task to know which leads are to be connected together to form the proper groups, but a study of some of the connections will reveal that the job is not so hard. Figure 333 shows the phases properly connected, and the six leads from the three phases ready for connection in star or in delta. Figure 334 shows the completed stator winding. The whole winding is covered with an insulating varnish which holds out moisture.

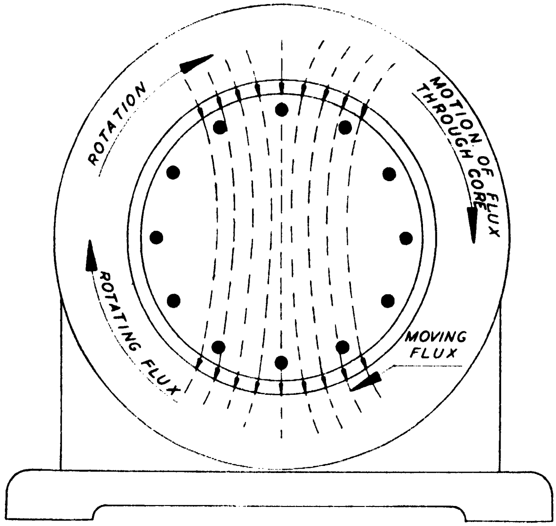


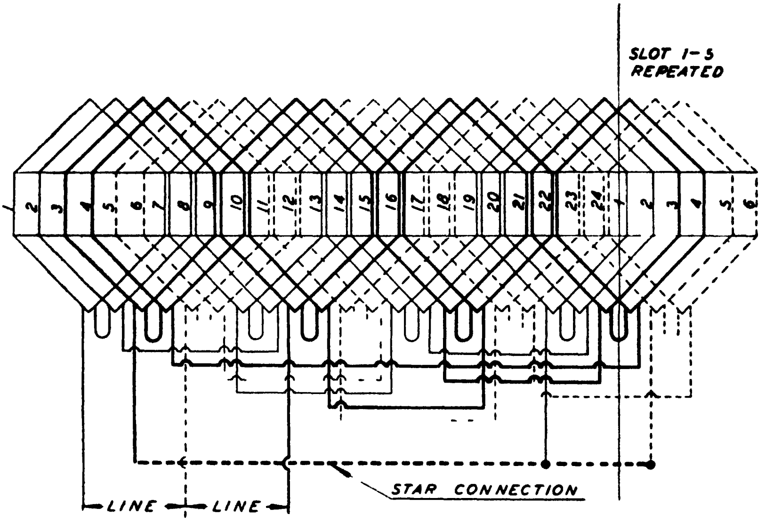
FIG. 336

The lead wires extend through the side of the frame.

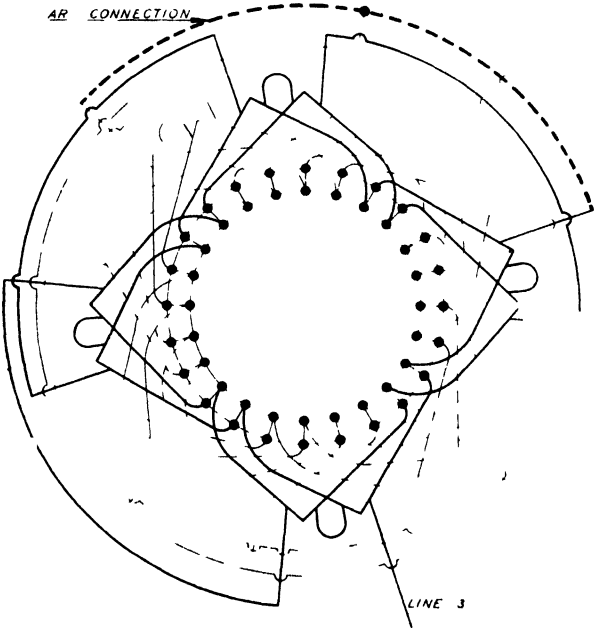
The winding on the stator is the field winding of the A.C. motor. There are no salient poles, however, as there are on D.C. motor frame (see Fig. 335). In fact as we shall see later the magnetic field produced in the stator is a revolving field: the flux lines move through the iron core by rotation as shown in Fig. 336.

66. STATOR WINDING:

Let us examine a little more carefully the winding on a three-phase motor stator. There are several ways in which windings



3 PHASE, SINGLE CIRCUIT STAR MOTOR CONNECTION
FIG 337



3 PHASE SINGLE CIRCUIT STAR MOTOR CONNECTION
FIG 338

may be pictured. When all of the coils are shown in a picture the tracing of currents through phases is not always easy. Fig. 337 is a plan drawing of a three-phase star-connected stator winding. The phases are definitely shown, and the pole areas are defined.

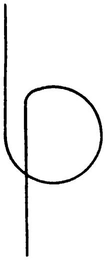


FIG. 339

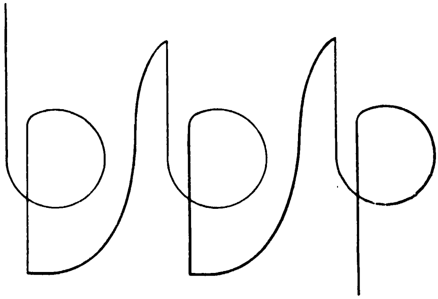


FIG. 340

In Fig. 338, the same winding is shown in a circular type of drawing. Here the picture is a bit more confusing. Both of these pictures show the slots, coil span, top and bottom sides of coils, etc.

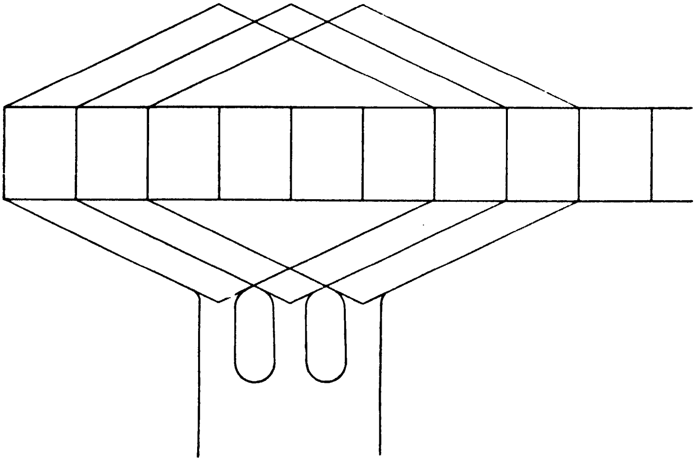
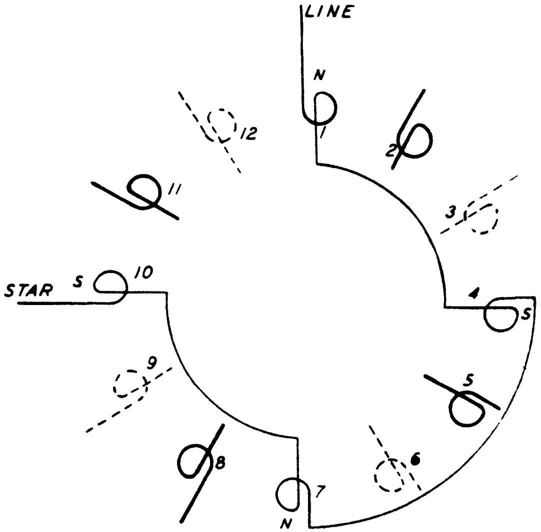


FIG. 341

For the sake of simplicity we shall use here another type of winding diagram, which we shall call the symbolic diagram. Each coil is represented by the symbol shown in Fig. 339, and two or more coils joined in series to form a pole group for any one phase could be shown as in Fig. 340, which has the same meaning as Fig. 341, the plan diagram. We shall, however, use the symbol in Fig. 339 to indicate either a single coil per pole, or several coils per pole.

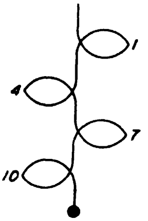


ONE PHASE OF A 3 PHASE
SINGLE CIRCUIT STAR CONNECTION

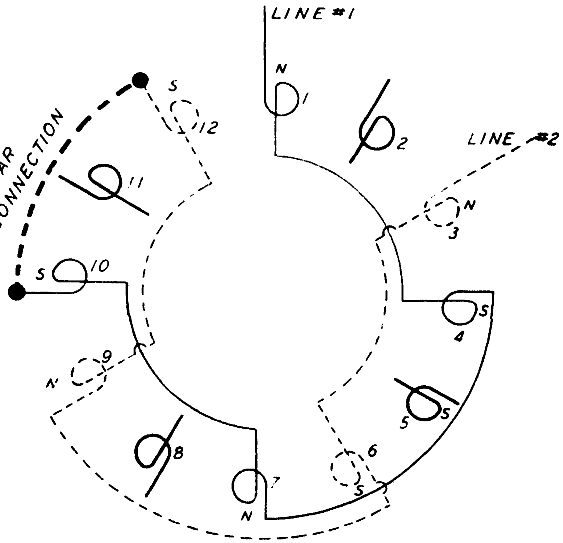
FIG. 342

Another feature which it is hoped the student will understand is that stator windings may be single-circuit, two-circuit, three-circuit, etc., as will be shown in the drawings following.

Stator windings do not all have the same number of coils per pole. The number varies with the make of the machine. But in general, machines are so designed as to have the same number of coils per pole, for each pole. Occasionally, it may be necessary to use a stator with a number of slots that will not permit this. For example, a stator having 45 slots does not adapt itself readily for a three-phase four-pole winding. Since there are three phases, each phase will use one-third of the slots, or fifteen. But as there are four poles, we cannot assign four slots to each pole, since this would take sixteen.



STAR CONNECTION
FIG. 343



TWO PHASES CONNECTED OF A 3 PHASE SINGLE CIRCUIT STAR STATOR WINDING CONNECTION
FIG. 344

It is therefore necessary to assign three slots per phase to one pole, and four slots per phase to the other three poles.

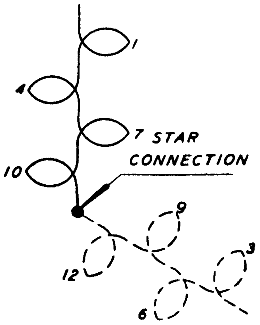
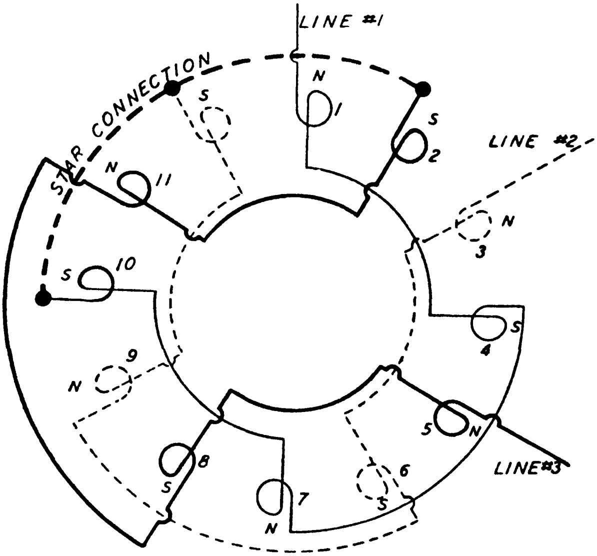


FIG. 345



COMPLETE 3 PHASE, SINGLE CIRCUIT STAR STATOR WINDING CONNECTION

FIG. 346

This will produce an unbalanced arrangement, but the unbalance is not serious enough to make it wholly undesirable.

The first drawing (Fig. 342), represents a three-phase four-pole, single-circuit stator. The three phases are distinctly shown, but only one is connected. Note that alternate

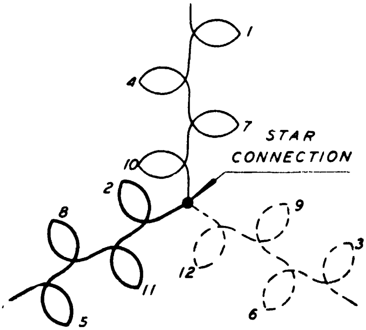
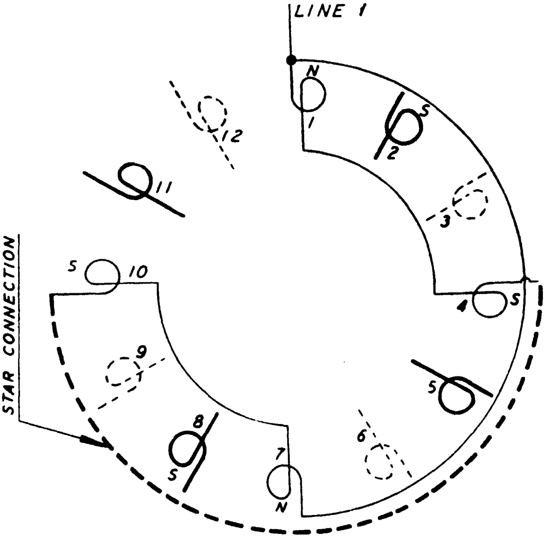


FIG. 347



ONE . PHASE OF A 3 PHASE
2 CIRCUIT STAR CONNECTED MOTOR

FIG. 348

coils are connected in reversed fashion to produce opposite polarity of field poles. The several coil groups are numbered, and a schematic wiring diagram appears below (Fig. 343).

Fig. 344 shows two phases connected together. Note that the second phase begins with coil group 3, so that between the two phases there is a displacement of 120° E. And note, too, that the finish ends of the two phases are connected together which indicates that this three-phase stator winding is to be a "star" three-phase. The star connection of the

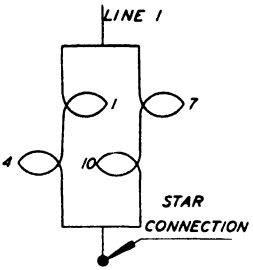
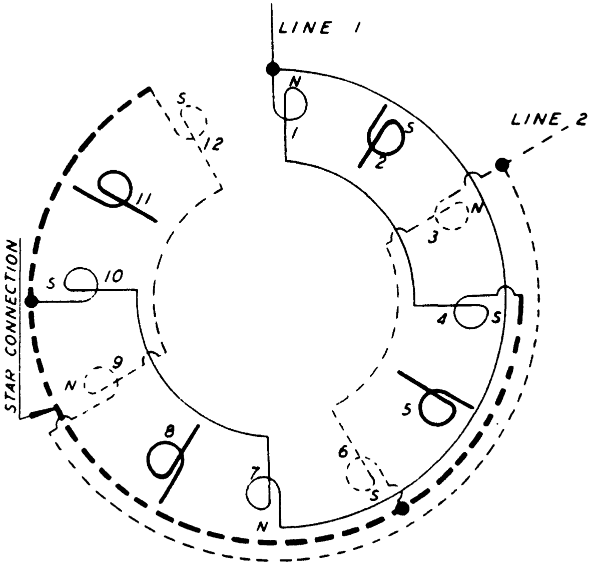


FIG. 349



2 PHASES OF A 3 PHASE, 2 CIRCUIT STAR CONNECTED MOTOR

FIG. 350

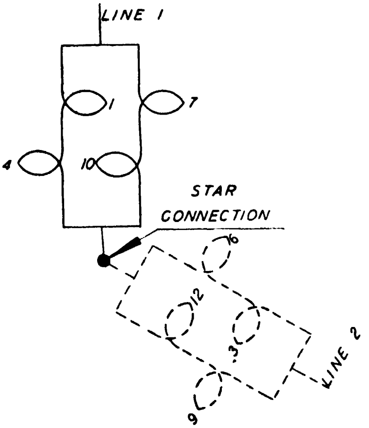
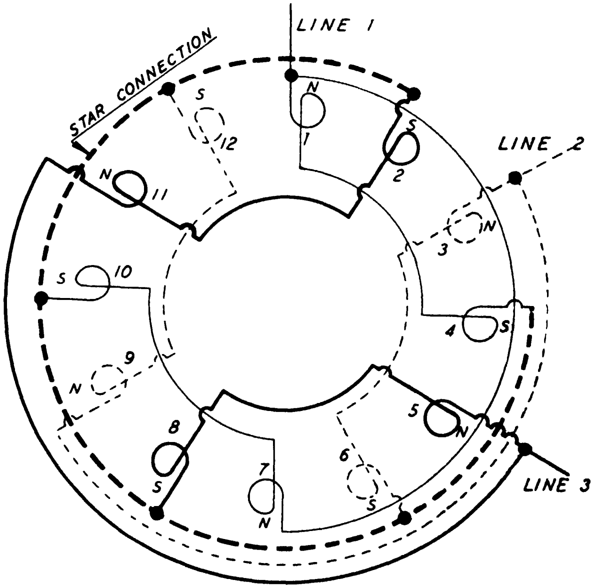


Fig. 351



3 PHASES OF A 2 CIRCUIT, STAR CONNECTED 3 PHASE MOTOR

Fig. 352

two phases now connected is shown by a dotted line. The schematic diagram (Fig. 345) again shows the two phases properly connected.

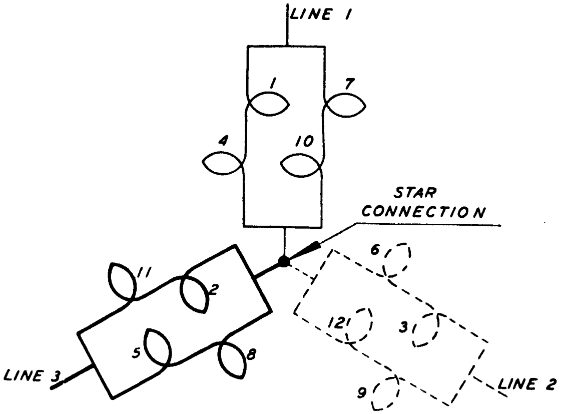
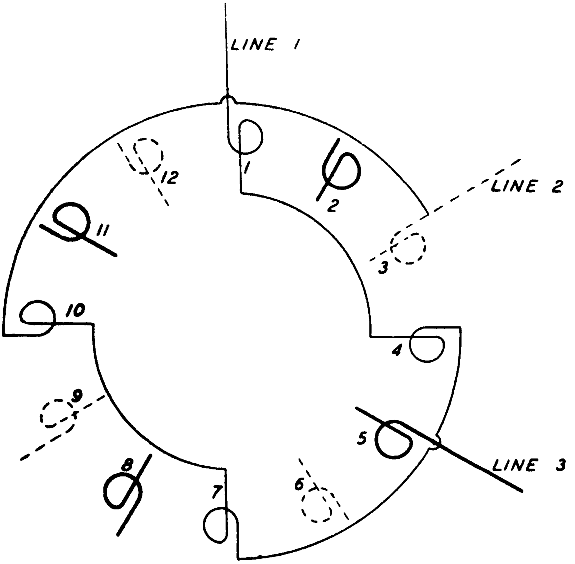


FIG. 353



ONE PHASE OF A SINGLE CIRCUIT DELTA CONNECTED 3 PHASE MOTOR

FIG. 354

The third phase is started at coil group 5, thus allowing a 120° E. displacement from phase 2. And the finish end is connected to the common "star" junction. See Fig. 346. The schematic diagram (Fig. 347) is also complete. The line wires are shown correctly joined to the three starting-ends of the phases.

The same three-phase stator winding can be arranged for a two-circuit (or parallel) connection as is shown in the drawings following. If the single-circuit star connection is used for a given voltage, say 440 volts, the two-circuit star connection is used for half the given voltage, or 220. In this manner it becomes quite easy to change the winding of a three-phase motor to operate on different voltages without disturbing the coils. Of course the winding must be first studied to make certain that a connection for a higher or a lower voltage operation is practicable in the given case.

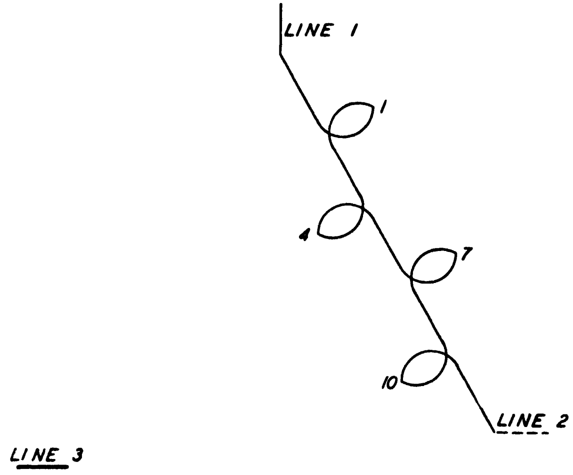
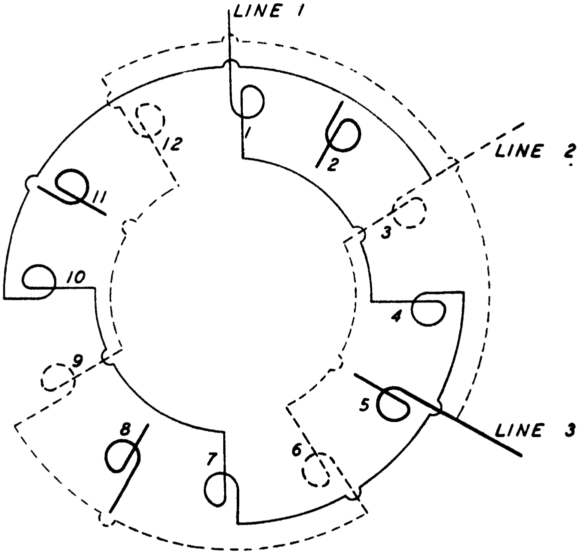


FIG. 355

In the two-circuit arrangement there are two leads connected to each line wire, also there are two leads from each phase to make up the star junction. This is because in the two-circuit arrangement the coils for the four poles in each phase are not joined in series. Instead, two are joined in one series group, and two are joined in a second series group. Then the two groups are connected in parallel. See Figs. 348,



TWO PHASES OF A 3 PHASE SINGLE CIRCUIT DELTA CONNECTED MOTOR

FIG. 356

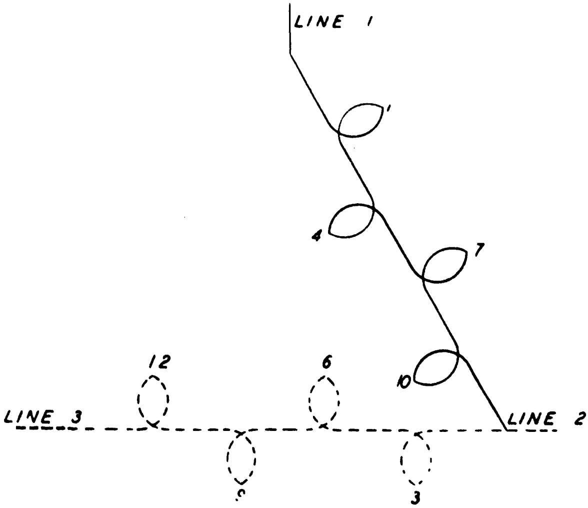
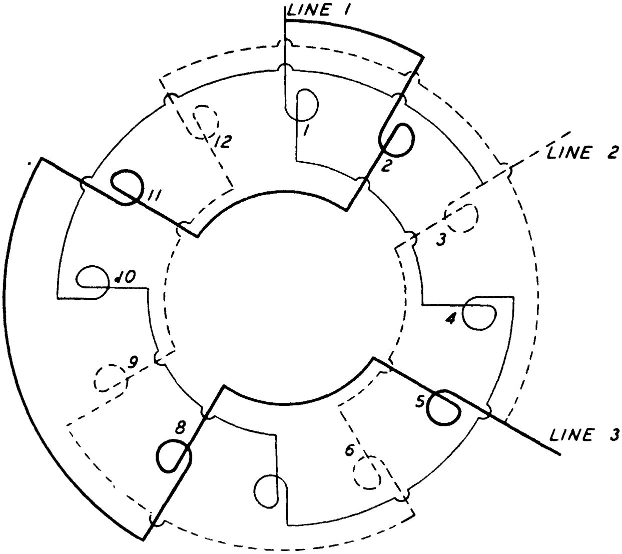


FIG. 357



THREE PHASES OF A 3 PHASE SINGLE CIRCUIT DELTA CONNECTED MOTOR

FIG. 358

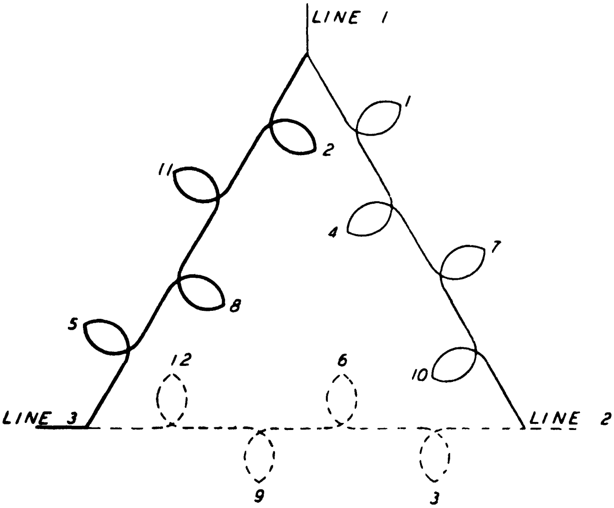
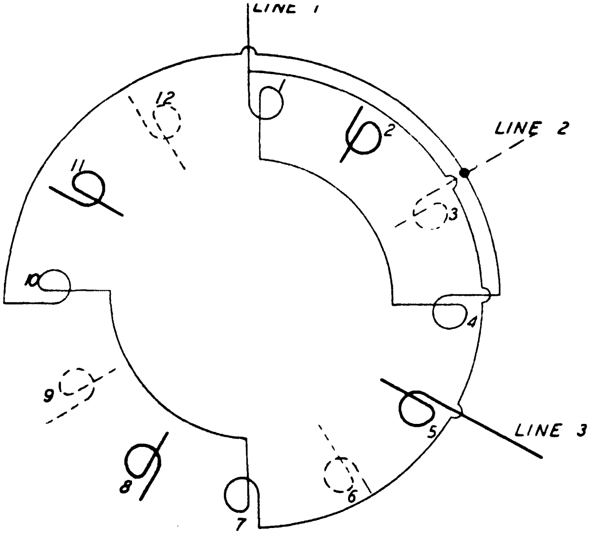


FIG. 359

349. Each line wire, therefore, feeds half of its current to the first two poles and the other half of its current to the other two poles. And again the "star" junction consists of the common connection of the finish ends of all phases.

Figs. 350-53 respectively show two phases and all three phases properly connected for a two-circuit three-phase four-pole star winding.

Now let us arrange this same winding for a single-circuit delta four-pole stator. Figs. 354-55 show the poles of one phase properly connected. Note that the connection of the poles within the phase is no different than before.



ONE PHASE OF A 3 PHASE TWO CIRCUIT DELTA CONNECTED MOTOR

FIG. 360

Figs. 356-57 show two phases properly connected within the phases and to the line wires. Note now, however, that the finishing end of phase 1 and the starting-end of phase 2 are correctly joined together and to the line wire 2. Similarly in Figs. 358-59 the finishing-end of phase 2 and the starting-end of phase 3 are joined together and to the third line wire; also the finish of phase 3 joins with the start of phase 1 at line wire 1 to close the delta.

To arrange this winding for a two-circuit three-phase delta, the four poles in each phase are arranged so as to put the first two in series, the other two in series, and the two series groups in parallel. Then each phase is connected as before, finishing-end of one to the starting-end of the next, etc. Drawing for one phase, two phases, and the entire winding show this in Figs. 360-65. There is, of course, no reason why this same winding could not be arranged as a four-circuit three-phase star or delta winding. The coils for the four poles in each phase would merely need all to be connected in parallel as is shown in Figs. 366-67. Such a stator would then be operated at ¼ voltage, or 110 volts.

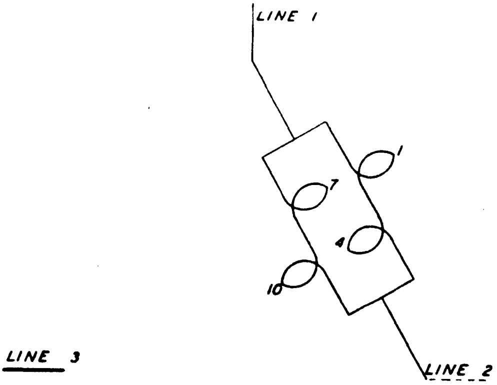
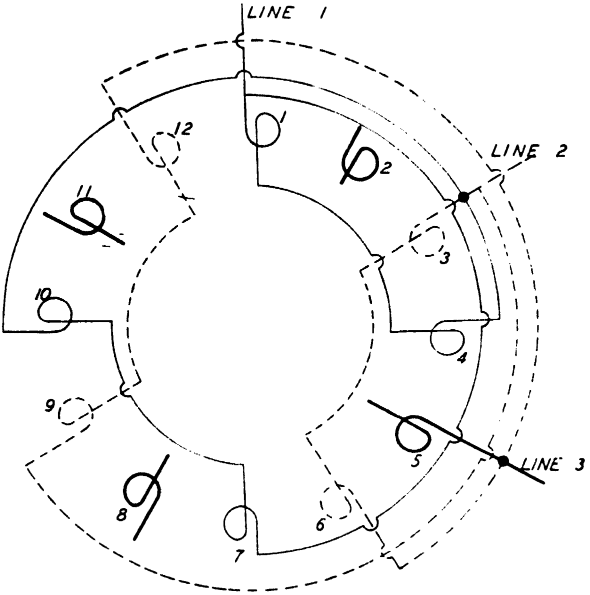


FIG. 361

67. THE THREE-PHASE ROTOR:

The kind of rotor used inside a three-phase stator really determines the kind of motor that results. There are three distinct types of rotors: the squirrel-cage rotor, the wound rotor, and the synchronous rotor.

The simplest rotor from the standpoint of construction and maintenance is the squirrel-cage rotor. It consists of a



TWO PHASES OF A 3 PHASE TWO CIRCUIT DELTA CONNECTED MOTOR

FIG. 362

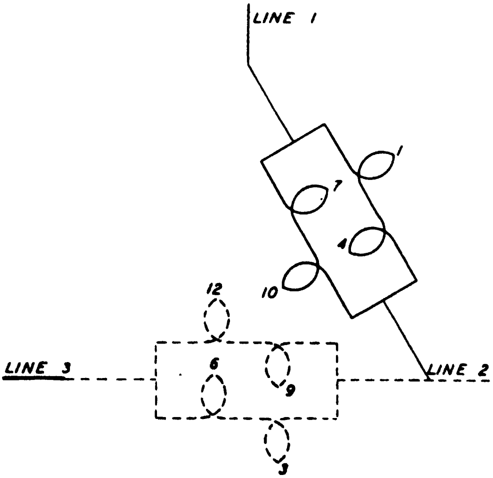
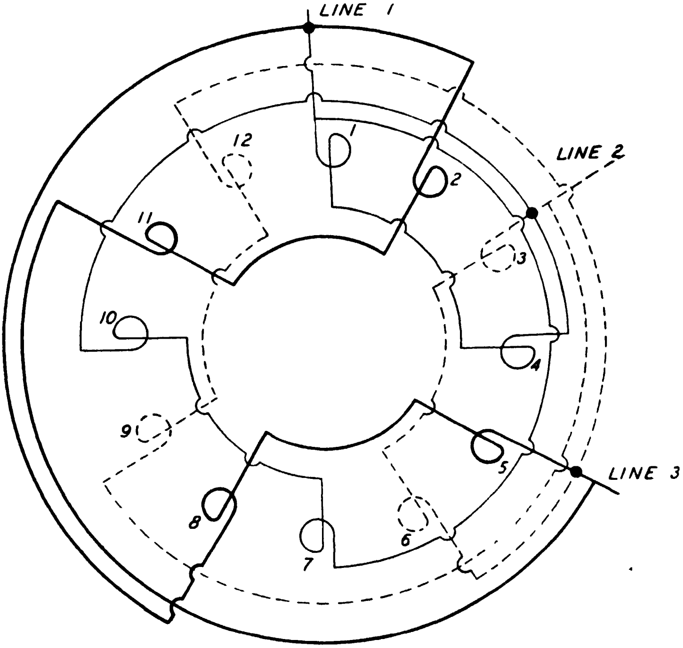


FIG. 363



3 PHASES OF A 3 PHASE 2 CIRCUIT DELTA CONNECTED MOTOR

FIG. 364

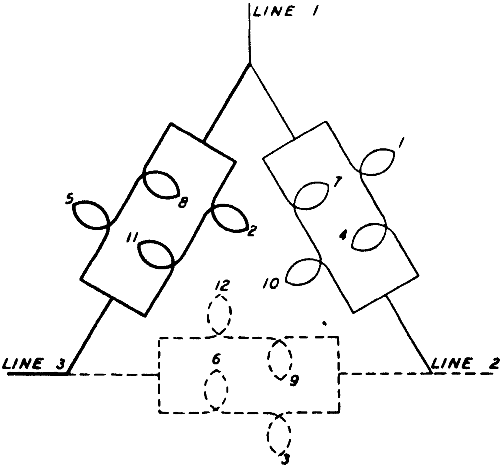


FIG. 365

shaft on which is mounted a laminated silicon steel core. There is little difference between a three-phase squirrel-cage rotor (Fig. 368) and the single-phase squirrel-cage rotor. In the most recent types the bar and end rings are cast into place rather than set mechanically. Casting also does away with soldered or welded joints between bars and rings. See Figs. 369-70. Fan blades are added on each side of the rotor to assist ventilation.

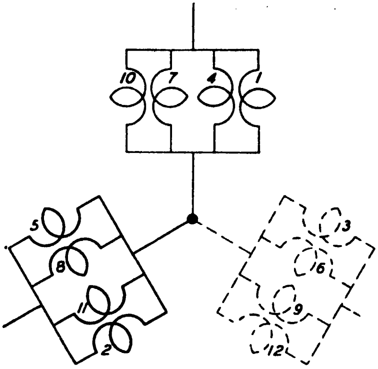


FIG. 366

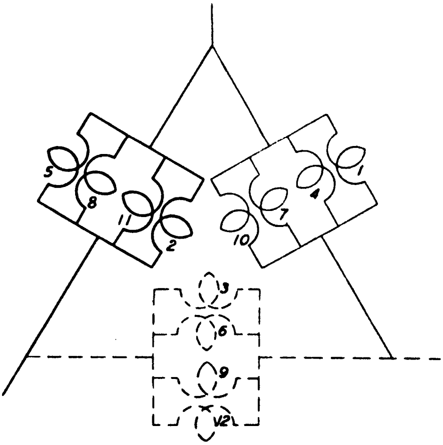


FIG. 367

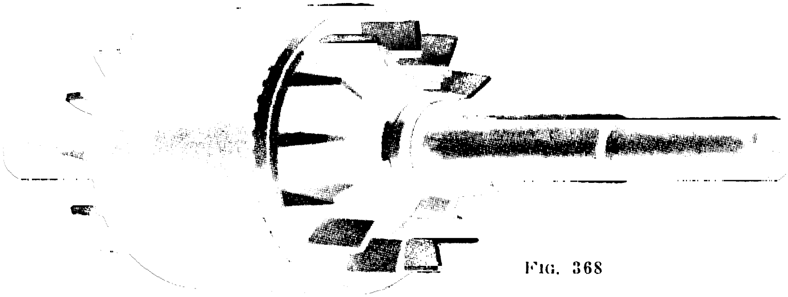


FIG. 368

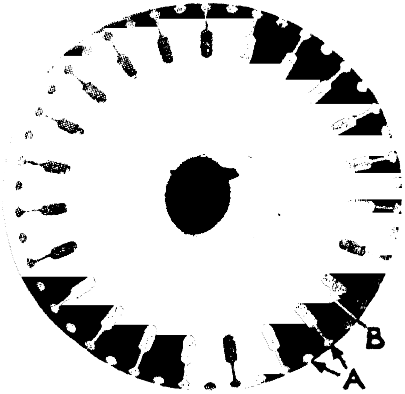


FIG. 369

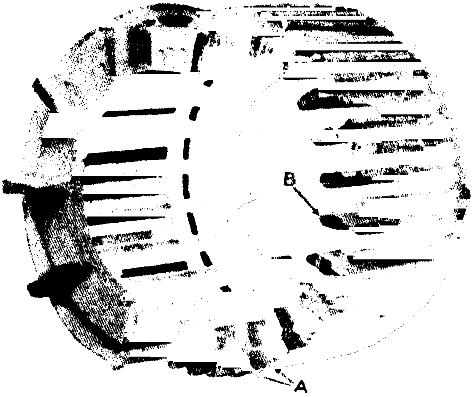


FIG. 370

The squirrel-cage rotor properly assembled when placed inside the three-phase stator gives a three-phase squirrel-cage induction motor. See Fig. 371.

Like the squirrel-cage rotor the wound rotor has a laminated core (Fig. 372) mounted on a shaft. The winding, however, is different. In the squirrel-cage rotor it consists of bare copper bars whose ends are fastened to copper rings. The wound rotor is just what its name states it to be. That is, the winding is made of coils similar to those used in a direct current armature except that the leads do not connect to commutator bars. Each coil is made up of a number of turns of insulated copper wire for the smaller rotors and insulated copper bars (Fig. 373) for the larger rotors. The coils are well insulated from the core to prevent possible leakage of current from a coil to the core, in other words "grounding."

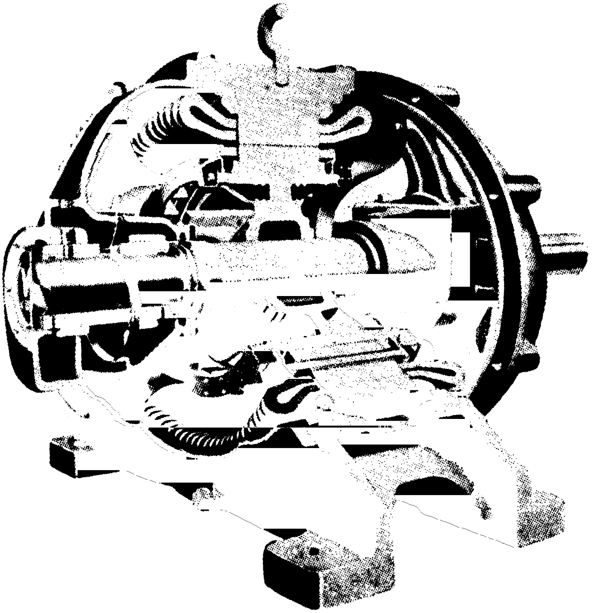


Fig. 371

The winding may be connected like the stator: star or delta and single or multiple circuit. Figs. 374 and 374A show one phase of a single-circuit star connection. Figs. 375 and 375A show the three phases of a three-phase single-circuit star-connected rotor. Examination of the drawings show that

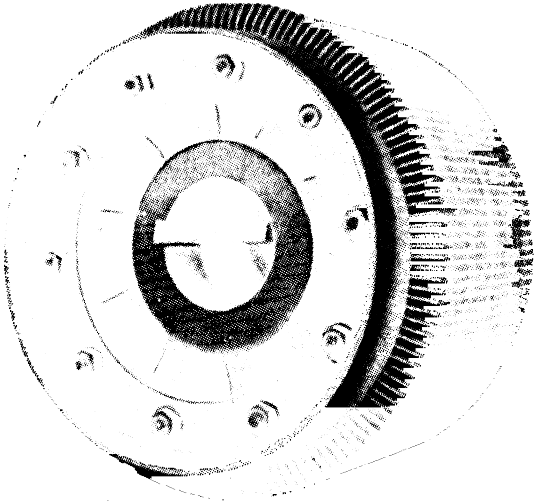


FIG. 372

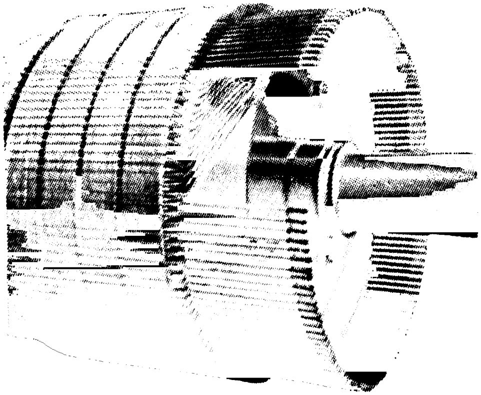
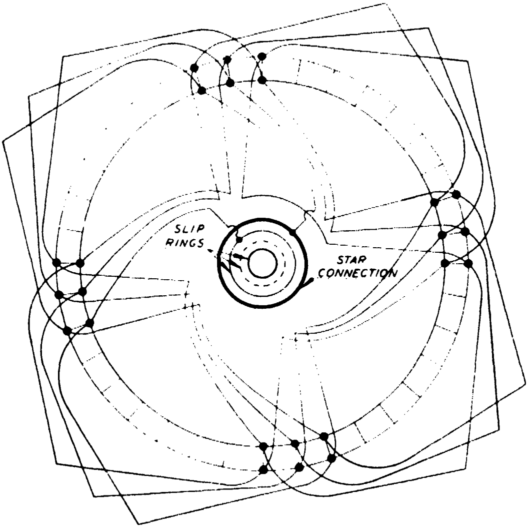


FIG. 373

this winding is a wave or series winding similar to the wave winding of a direct current armature. A lap winding could be used instead of the wave but the wave winding requires fewer end connections, hence the wave winding is more commonly used.



ONE PHASE OF A 3 PHASE WOUND ROTOR CONNECTION SINGLE CIRCUIT STAR

FIG. 374

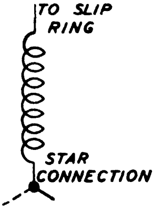
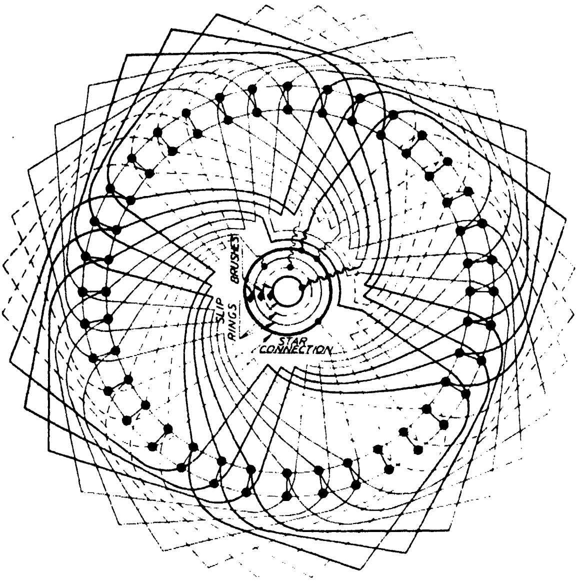


FIG. 374A

Wound rotors may be placed in two groups: those having slip rings and the type with a short-circuiting device, which automatically short-circuits the winding when the rotor attains full-load speeds. Of the two the slip-ring type is more widely used.

In the slip-ring type of rotor, the leads (from the three phases) are brought out to three bronze or steel rings called



3 PHASE ROTOR WINDING CONNECTED SINGLE CIRCUIT STAR

FIG. 375

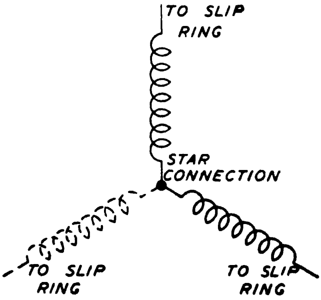


FIG. 375A

slip or collector rings. (Figs. 376, 377). They are carefully insulated from one another and from the shaft on which they are mounted. Ordinarily the rings are placed close to the rotor winding in order that the lead wires from the winding to the rings may be as short as possible. The purpose of the collector ring is to permit connection of resistance into the

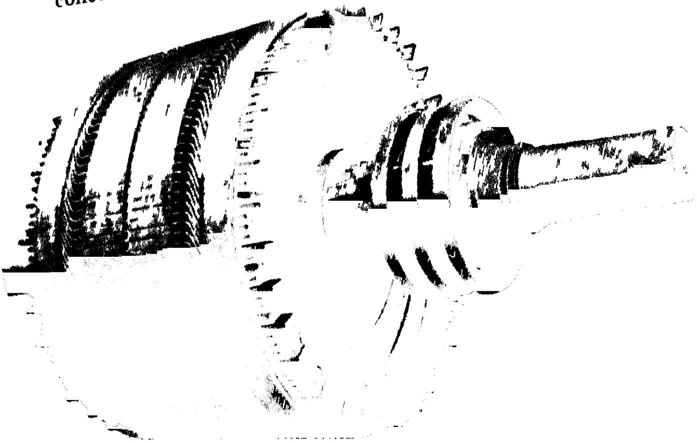


FIG 376

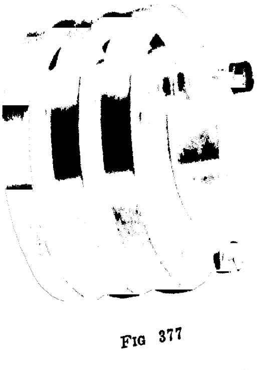
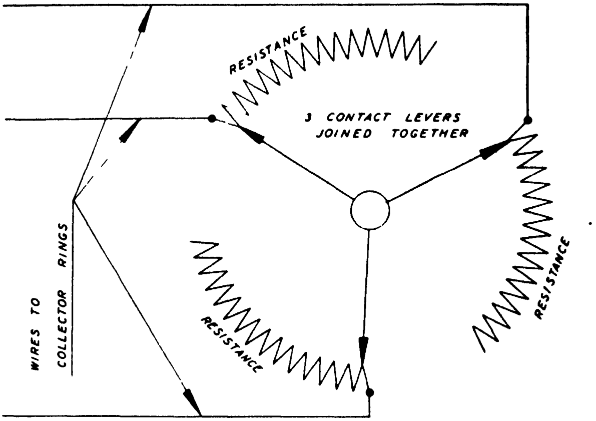


FIG 377

rotor circuit if desired. Hence brushes are needed to make contact with the collector rings. The brushes may be metal (copper or brass) or carbon, and they may be placed at any convenient location.

A three-phase rheostat may be connected to the collector rings. Such an arrangement (Figs. 378, 379) permits the control of the current induced in the rotor winding, which in turn varies the speed of the motor below normal full-load speed. The range of speed variation may be from 50% full-load speed to full-load speed. The rheostat does not make possible increase in speed above the normal full-load rating of the motor.



3 PHASE ROTOR RHEOSTAT

FIG. 378

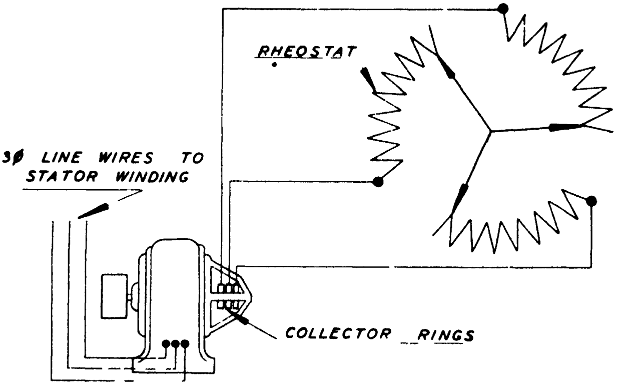


FIG. 379

The wound rotor with the short-circuiting device is so arranged that a high resistance winding can be short-circuited to produce a low resistance winding similar to a squirrel cage after the rotor has attained about 70% full speed. The rotor also has a squirrel cage in addition to the high resistance winding. Such an arrangement makes possible a low starting current without an external starting device. During the starting-period the motor has wound rotor characteristics and during the running period it has characteristics very much like the squirrel-cage induction motor.

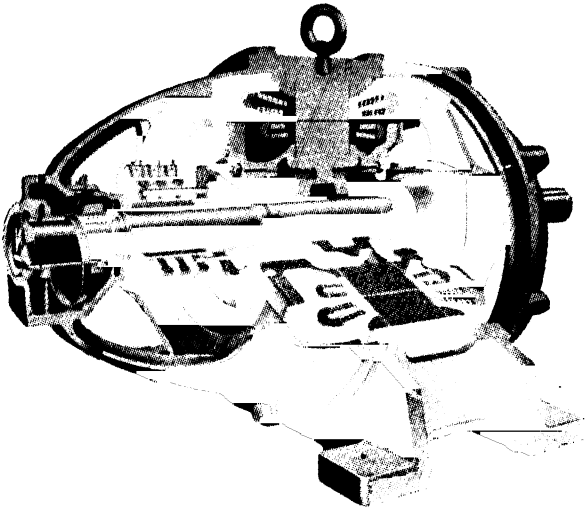


FIG. 380

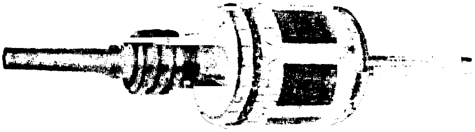


FIG. 381

The slip-ring rotor placed inside a stator produces a motor (Fig. 380) called a wound rotor induction motor. It has characteristics that differ from the squirrel-cage type of induction motor and which adapts it to certain kinds of service, such as heavy torque starting duty.

The synchronous rotor differs from the other two both in construction and in operation. A study of Fig. 381 will show the difference in construction. The core is made of laminated silicon steel just like the other types of rotors and is mounted on the shaft in the same way. Instead of having slots placed equidistant around the core, the synchronous rotor has poles similar to the pole pieces on a direct current motor frame.

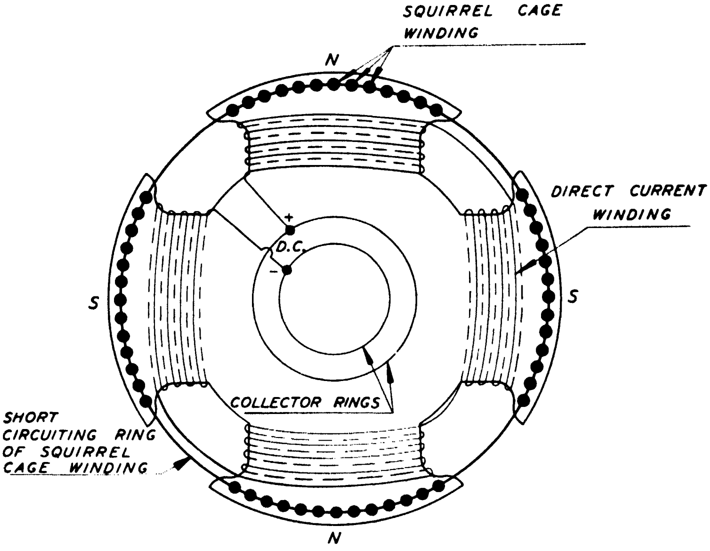


Fig. 382

Each pole piece is equipped with a winding, which is built like the shunt field winding of a direct current machine. These field windings are connected so that adjacent poles are of opposite polarity. See Fig. 382. The leads are then connected to slip rings, which make possible connection to the line wires. The line wires in this case must furnish direct current, which results in permanent north and south poles. The current fed to the stator winding is alternating. Therefore, both direct and alternating current are necessary for the operation of a synchronous motor.

In addition to the direct current field coils, the rotor is usually equipped with a light squirrel-cage winding (visible in Fig. 382). The purpose of this winding is to act as a starting winding. It remains intact during the running period. Without this winding the synchronous rotor could not easily be started. There is no electrical connection between the direct current field winding and the squirrel cage winding. Connection with the source of direct current is not made until the motor has attained full speed. And to permit field current variation a field rheostat is included in the field circuit. The ordinary alternator may be adapted for use as a synchronous motor (see Section 88). Although designed primarily to operate as an alternator, nevertheless it can be used as a synchronous motor. Usually such alternators (at least in the smaller sizes), are self-excited, and the field poles are stationary.

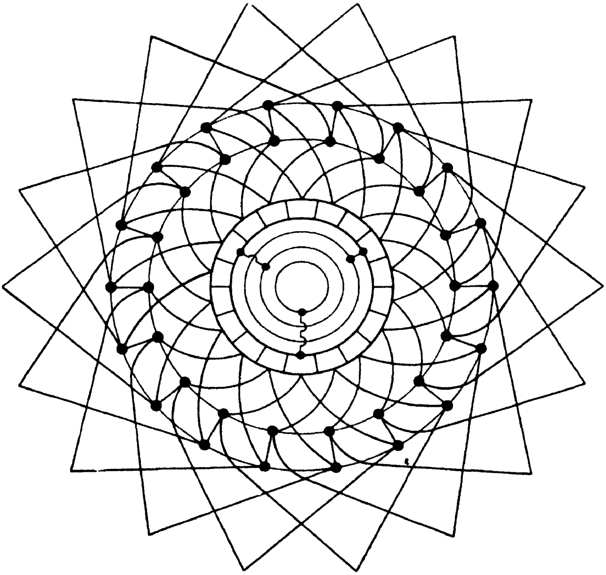


FIG. 383

The rotor in this machine is built (see Fig. 383) just like a direct current armature and in all respects looks like a direct current armature, except that in addition to the commutator, there is a set of slip or collector rings which are connected at proper intervals to the armature winding. For the three-phase machine the winding is usually tapped at three equidistant points. The frame for this machine is identical with that of a direct current machine in that it has pole pieces with a shunt field winding as shown in Fig. 384.

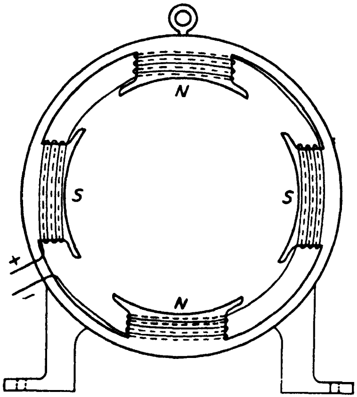


FIG. 384

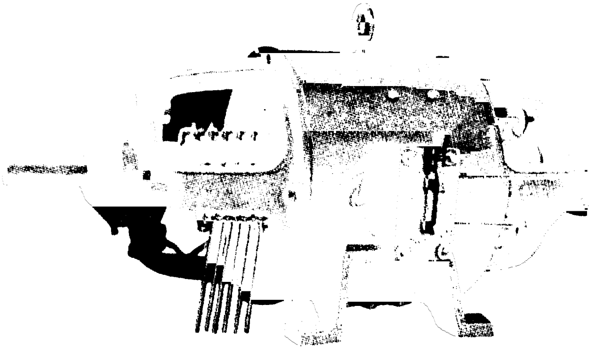


FIG. 385

Fig. 385 shows what is sometimes called a double current generator. This machine is built similar to the synchronous motor just described. It is a very flexible unit, ideal for laboratory purposes, since it can be used as an A.C. or a D.C. generator, an A.C. (synchronous) or a D.C. motor, a synchronous condenser, or a rotary converter. Observe in the one picture that the rotor (armature) winding is tapped at several places, the leads running to slip rings, which permits the use of this machine for single-phase, two-phase, three-phase, and in some cases six-phase and twelve-phase. The other picture shows the D.C. side of a similar machine, the coil leads running to commutator segments. A more detailed explanation is given in the section on the rotary converter.

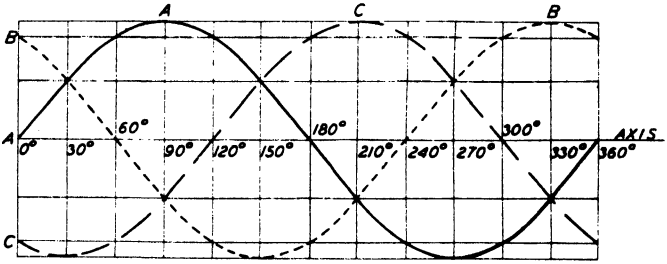
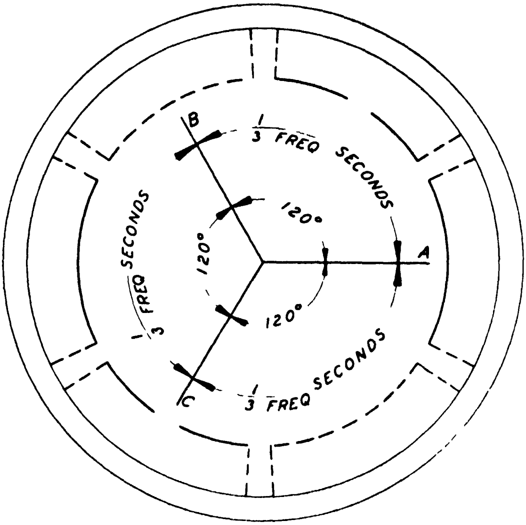


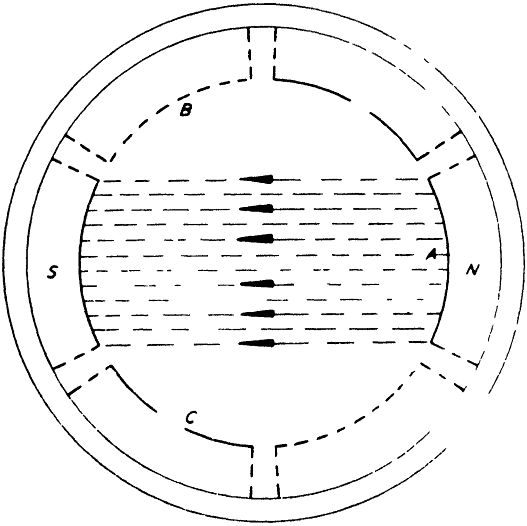
FIG. 386

68. THE REVOLVING FIELD:

Assume the stator winding connected to a three-phase line. Current flows from the line through the winding. A study of Fig. 386 shows the relationship of the current values in the various phase wires of the line. Stating it in another way, phase *A* reaches its positive maximum value at a given instant, 120° later phase *C* reaches its positive maximum value, and 120° after this, phase *B* reaches its positive maximum value. If we assume a frequency of one cycle per second and starting with phase *A* at its positive maximum, phase *C* will reach its positive maximum 1/3 of a second after phase *A*, and phase *B* will reach its positive maximum 1/3 of a second after phase *C*. For a frequency of 60 cycles per second the time interval between positive maximum values of phases will


B
$\frac{1}{3}$ FREQ SECONDS
120°
120°
120°
A
$\frac{1}{3}$ FREQ SECONDS
C
$\frac{1}{3}$ FREQ SECONDS

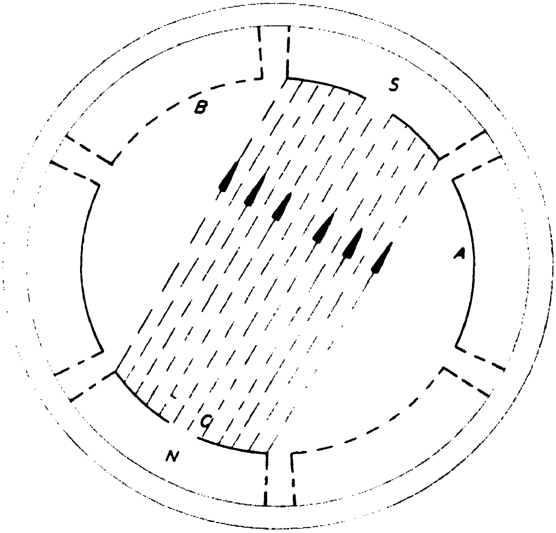
2 POLE 3 PHASE
FIG. 387



2 POLE 3 PHASE
FIG. 388

be greatly reduced, being 1/180 of a second. See Fig. 387.

When phase *A* is at its maximum, the greatest number of lines of force are set up by the poles of this phase. Fig. 388 shows a two-pole three-phase stator with the current at its maximum through phase *A*. Referring back to Fig. 386, it will be noted that when phase *A* is at its maximum (positive), phase *B* and *C* are at half-values (negative). Hence there is current flowing through the windings of phases *B* and *C* and lines of force are set up, but not of maximum strength, and not shown in Fig. 388. Exactly 120° E. after phase *A*, phase *C* reaches its positive maximum value (Fig. 386). Hence at that instant phase *C* sets up the greatest number of lines of force in all its poles. Note that the strong *N* and *S* poles have shifted from phase *A* to phase *C*. See Fig. 389. *B* and *A* are not shown. Similarly phase *B* reaches its maximum positive value 120° E. after phase *C*, with the result that

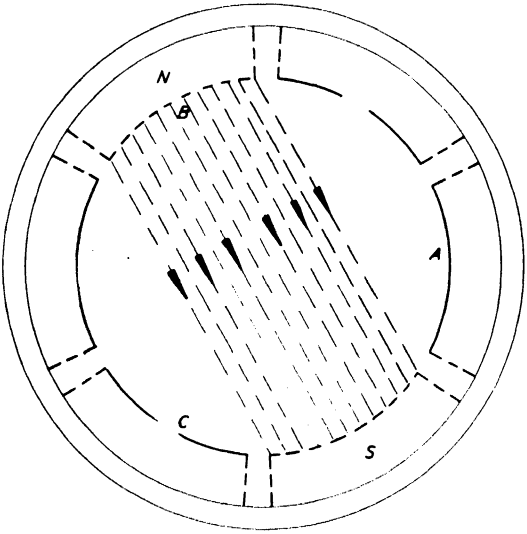


2 POLE 3 PHASE

FIG. 389

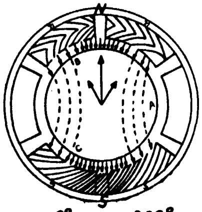
the strong *N* and *S* poles have shifted from phase *C* to phase *B*. See Fig. 390. (*C* and *A* are not shown.)

In Figs. 391-402, an attempt is made to show how the poles shift or how the revolving of the field in the three-phase motor is accomplished during one complete cycle of the three-phase current. The drawings show what takes place every 30° or for a one cycle frequency what takes place every $\frac{1}{12}$ of a second; or again for a 60-cycle what takes place every $\frac{1}{720}$ of a second. A careful study of the drawings will show how the field of the poles moves at a uniform rate around the stator. Start with Fig. 391 and note the position of the *N* pole, then note the position of the *N* pole through the other diagrams. If followed in order, Figs. 391, 392, 393, etc., it will be seen that the field revolves around the stator. This phenomenon is known as the revolving field.

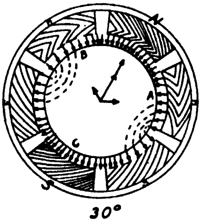


2 POLE 3 PHASE

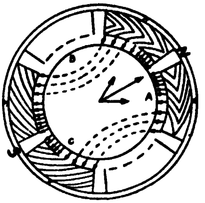
FIG. 390



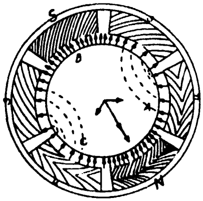
0° 360°



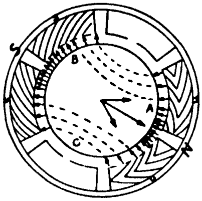
30°



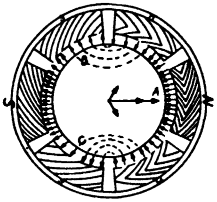
60°



150°

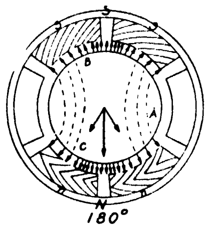


120°

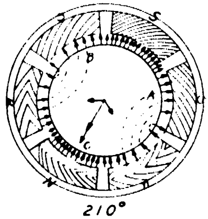


90°

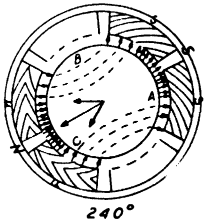
FIGS. 391 to 396



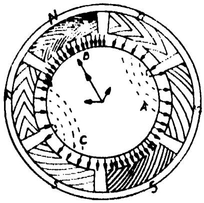
180°



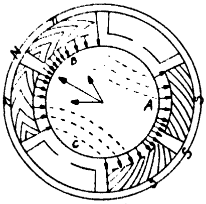
210°



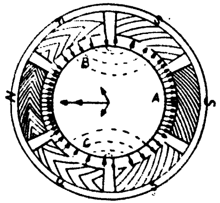
240°



330°



300°



270°

FIGS. 397 to 402

69. CAUSE OF ROTATION:

If a small steel ball bearing is placed inside the stator it will be pulled around the stator by the revolving field. A magnetic compass placed in the middle of the stator rotates at the same speed with which the field is rotating around the stator. The *S* pole of the compass will be attracted by the *N* pole of the stator. Therefore, regardless how fast the field revolves the compass needle follows at the same rate. This is similar to what happens in the synchronous motor, since the field poles are definitely north and south, being made so by the direct current.

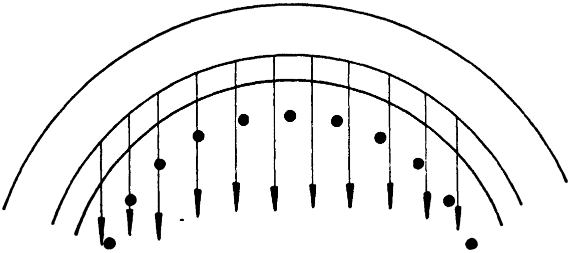


Fig. 403

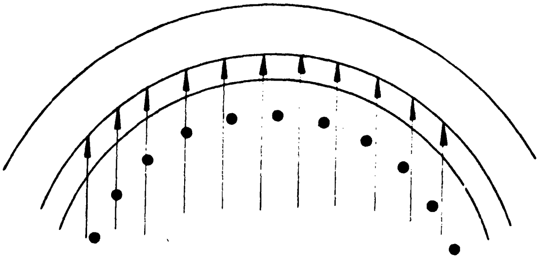


Fig. 404

Let us see how the revolving field affects the rotor of an induction motor. If the line switch is closed to permit a current to flow through the stator winding, a revolving field will be set up. The instant the current passes through the stator winding, the lines of force set up in the stator pass through the rotor iron cutting the secondary winding and setting up an E.M.F. in the rotor by transformer action. Figs. 403, 404 are intended to show this alternating flux cutting the rotor conductors. The E.M.F. forces a current through the closed winding of the rotor, and the current in turn sets up lines of force, producing a north and a south pole on the rotor, as illustrated in Fig. 405. Note that these poles set up by transformer action are directly under the poles of the stator. The position of the poles on the rotor with respect to the poles on the stator is such that the forces act directly in line with the center of the shaft and fail to produce motion.

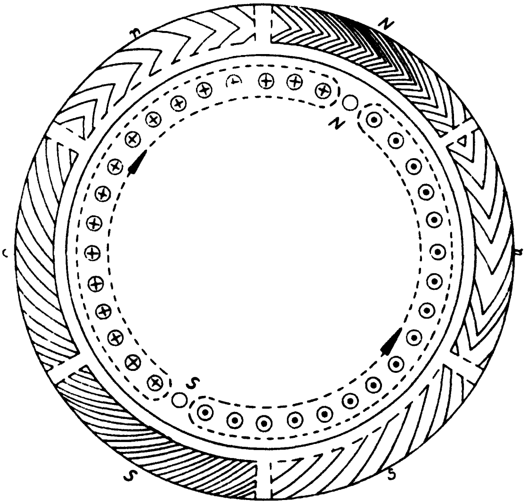


FIG. 405

But we are here dealing with a revolving stator field. As this field revolves the lines of force cut the rotor bars and a speed E.M.F. is also generated. This result is just the same as though the bars were moving and the field were stationary. Hence in addition to the E.M.F. and current set up by transformer action, an E.M.F. and current are also set up by ordinary generator action. Fig. 406 shows the position of the poles on the rotor due to speed E.M.F. and current. A comparison of Fig. 405 with Fig. 406 will show that the position of the poles due to transformer and ordinary generator action are not the same, but are displaced by 90° E. Now both of these actions are present in the motor, with the result that the north pole of the rotor at the moment chosen somewhere between the positions shown in Figs. 405, 406. And similarly with respect to the south pole. Note, however, that the resultant pole is in such a position that the *N* pole of the

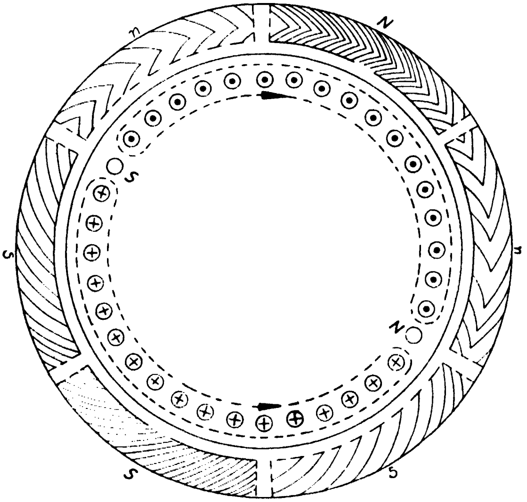


FIG. 406

stator attracts the *S* pole of the rotor and repels the *N* pole of the rotor. Similarly the *S* pole of the stator attracts the rotor *N* pole and repels the rotor *S* pole. Hence the cause of rotation. The position of the rotor and stator poles gives a short lever to the force between these poles with the result that there is torque during the starting-period.

70. SLIP:

When the rotor has come up to full speed a tachometer will show that it is running at a little less than synchronous speed. That is to say, if the frequency of the current in the stator winding is 60 cycles per second, the speed of the rotor may be that corresponding to a frequency of perhaps 58 cycles per second. Or again if the synchronous speed of a four-pole motor is 1,800 R.P.M. the actual speed of the motor may be 1,740 R.P.M. at full load. In all induction motors, whether squirrel cage or wound rotor, the actual speed of the motor is always less than the synchronous. Moreover, the speed also varies with the load. The difference between the synchronous speed and the actual speed is called the "slip," which can be found by the equation,

$$\%\ \text{slip} = \frac{\text{synchronous speed} - \text{actual speed}}{\text{synchronous speed}} \times 100$$

$$\%\ \text{slip} = \frac{1800 - 1740}{1800} \times 100$$

$$\%\ \text{slip} = \frac{60}{1800} \times 100 = 3.3\%$$

The actual rotor speed can never be as large as the synchronous speed. If we assume the rotor bars to move in exact synchronism with the flux lines of the stator, the bars could induce no speed E.M.F. since the lines would not cut the bars. But if the bars move more slowly than the flux lines, or, in other words, if the bars slip behind the flux lines as both rotate, then a speed E.M.F. and current can be induced in the rotor.

It is by means of slip that the rotor adjusts itself to a varying load. Assume that with half-load the rotor moves at 1,760 R.P.M. As full load comes on, the rotor tends to slow down, let us say, to 1,740 R.P.M. This added slip of 20 R.P.M. means that the bars are cutting through the flux 20 additional times per minute. Hence more voltage is developed by the rotor bars, more current flows in the rotor and this larger current gives the added torque needed to carry the additional load.

71. SPEED CONTROL:

We have just seen that the induction motor adjusts its speed to the particular load that it must carry at the moment, by increase or decrease of the slip. Of course, if the load is too great, the motor simply refuses to carry it, and "breaks down," that is, comes to a standstill. Moreover, the induction motor is a fairly constant speed motor. Any variations in speed due to load changes are limited to a narrow range. It is often quite desirable for industrial purposes that variable speed be attainable. It has already been shown that this is possible in the case of a slip-ring motor by use of a three-phase rheostat. But speed control for the squirrel-cage motor is not so easily arranged.

There are in general four methods that provide speed control with three-phase induction motors: (*a*) varying the rotor current in a slip-ring motor by means of external rheostat; (*b*) varying the frequency of the voltage impressed on the stator winding; (*c*) reconnecting the stator winding for a different number of poles; (*d*) using induction motors in "concatenation" (also called "cascade").

The first of these methods is applicable to slip-ring motors only, and has already been discussed. The second, varying the frequency, changes the speed in the same ratio as the frequency, as is seen from the equation,

$$\text{R.P.M.} = \frac{f \times 60}{P}$$

Commercial currents do not lend themselves to variable frequencies, so that it is necessary to install frequency-changers, which is done in many industrial plants. Thus, by means of motor-generator sets, frequencies of 120 or 180 for use on wood-working machines or grinders are obtained. The motor speeds are then double or triple those for 60-cycle currents in machines having the same number of poles. Thus synchronous speed for a four-pole machine is 1,800 on a 60-cycle frequency. It would be 3,600 on 120 cycles and 5,400 on 180 cycles. It is not desirable to use a motor designed to run on a 60-cycle current on higher or lower frequencies. The reactance of the coils is directly proportional to the frequency of the current, and therefore there are internal changes in current, flux, and heating that make it necessary to use motors specifically designed to operate on the prescribed frequencies.

Rearranging the stator winding to give a fewer or a larger number of poles also has disadvantages. It may not even be possible. Or, if possible, it is done at a sacrifice of motor characteristics and efficiency, especially when more than two speeds are required. The simplest rearrangement, and one that gives very satisfactory results at both speeds, is to connect the stator winding as a single-circuit delta for the larger number of poles, and as a two-circuit star for the smaller number of poles. This is shown in Figs. 407-410. The first two of these, show a single-circuit delta connection; the last two, the two-circuit star. Note that the change is made very simply. In Fig. 408, poles 1, 4, 7, and 10 are connected in series to form one phase. Tap *A* is taken at the middle of this series arrangement, and similarly, taps *B* and *C*, for the other two phases. The three line wires *X*, *Y*, *Z*, are connected

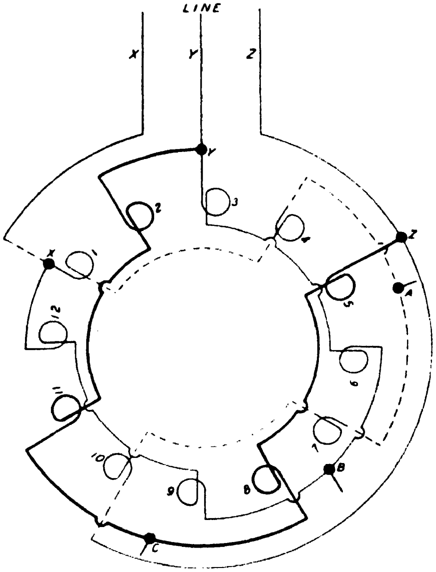


FIG. 407

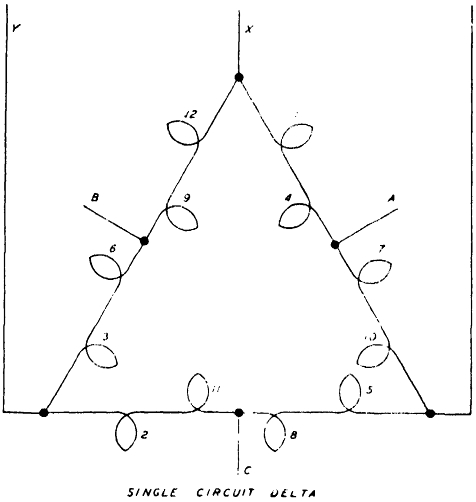


Fig. 408

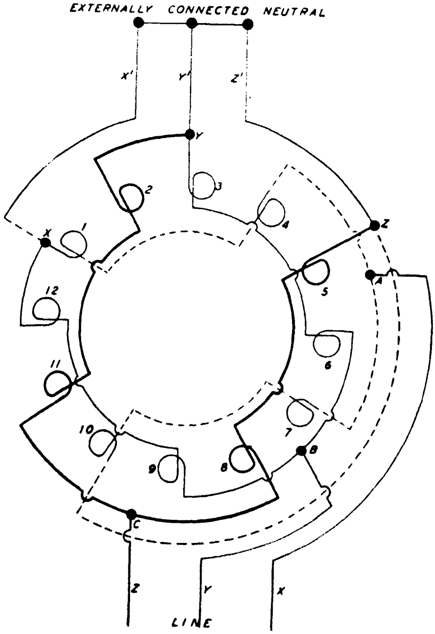
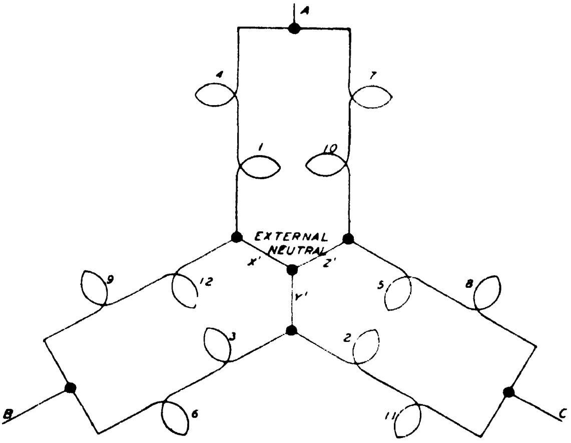


Fig. 409

to these mid-taps, *A*, *B*, *C*. The neutral of the star arrangement is obtained by short-circuiting the motor leads *X*, *Y*, *Z*, to which the line wires were previously connected. See Figs. 409, 410.

Two windings are sometimes placed on the same stator, for different numbers of poles, as for example, 18 poles and 12 poles, or 36 and 24, thus affording two different speeds. But only one winding is used at any one time and the cost of the motor is correspondingly greater. When the number of stator poles is changed a corresponding change must also be made in the rotor if the latter has a coil winding, but not if it is a squirrel cage.



2 CIRCUIT STAR

FIG. 410

Finally, the speed of motors can be varied by the method called "concatenation." Two or more motors can be so used, but it is necessary that all but one have wound rotors. The arrangement, as shown in Fig. 411, calls for the connection of the stator of the slip-ring motor to the line supply, and the connection of the primary of the second motor (which may be either squirrel cage or wound rotor) to the three slip rings of motor No. 1. The rotor of No. 2 is short-circuited. Also the shafts of the two motors are rigidly coupled together. The motors must therefore of necessity run at the same speed. Now the current in the stator of No. 2 is supplied by the rotor of No. 1. Hence the frequency of the current in the stator of No. 2 is the frequency of the current in the No. 1 rotor. The latter is determined by the slip of No. 1 rotor. In other words if the slip is 5%, the frequency of the No. 1 rotor current is 5% of the line frequency or,

$$f_2 = s_1 \times f_1$$

in which s_1 is the % slip of No. 1 motor. If f_1 is 60 cycles per second, then the current in No. 2 stator has a frequency of

$$f_2 = .05 \times 60$$
$$= 3.0 \text{ cycles per second.}$$

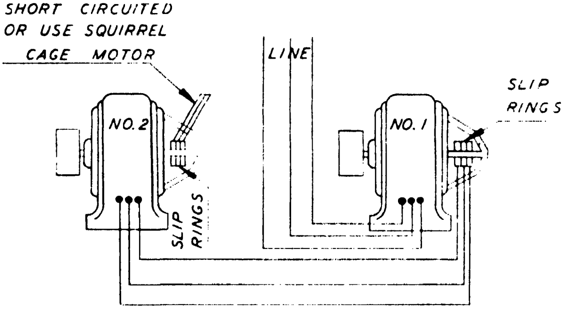


FIG. 411

This would of course result in a very low synchronous speed for motor No. 2 if it were free to run alone.

Without attempting a mathematical proof, the result of this arrangement of motors in terms of the resulting speed can be expressed by the equation,

$$\text{R.P.M.} = \frac{f \times 60}{P_1 + P_2}$$

f being the supply line frequency, P_1 and P_2 being the number of pairs of poles in the two stators.

It should be stated here also, that the slip rings of No. 1 motor may be connected to the stator of No. 2 to produce clockwise or counter-clockwise rotation. If No. 2 stator is connected to produce rotation in the same sense as No. 1, then the equation stands as above. If, however, No. 2 stator is so connected that it tends to turn oppositely to No. 1, then the above equation is

$$\text{R.P.M.} = \frac{f \times 60}{P_1 - P_2}$$

If the two stators have four poles each, either motor alone should run at 1,800 R.P.M. on 60-cycle mains. Concatenated so as to produce rotation the same way, the speed of the combination is

$$\text{R.P.M.} = \frac{60 \times 60}{2 + 2} = 900.$$

If the two were connected in opposite rotation fashion, the combination could not start by itself, but once started would tend to race, since in this case,

$$\text{R.P.M.} = \frac{f \times 60}{P_1 - P_2} = \frac{60 \times 60}{0} = \text{infinity}.$$

Hence with two motors having the same number of poles two practical speeds are possible, 1,800 and 900. In practice, the two stators are paralleled to the mains for the 1,800 speed. Of course, the No. 2 motor may also be a wound-rotor unit, in which case additional speed control of the system is afforded by a rheostat inserted into the No. 2 rotor. Two similar motors make possible full-load torque of the two motors together, at any speed obtainable without overload current in either stator. When directly concatenated the total output is 50% of the rated capacities of the two.

Motors having different numbers of stator poles can be concatenated, if desired, to give four different speeds, one of which is opposite in sense to the other three.

In a certain sense, motor No. 1 shows generator action, since its rotor supplies the current for the stator of No. 2. An induction motor can be used as a generator by driving it above synchronous speed by steam turbine or otherwise. As a motor, it takes current from the mains proportionate to the load it carries, and at a speed always below the synchronous. If now it be driven above synchronous speed, the rotor turns faster than the revolving field of the stator and hence the rotor currents are opposite to what they are as a motor. These opposite currents produce opposite rotor poles which in turn cause current to be generated in the stator. This current is a leading current and puts power back into the line mains. Of course, the line mains still have to provide the exciting current for the stator. Induction generators are sometimes used in central stations as auxiliaries.

72. THREE-PHASE MOTOR CHARACTERISTICS:

The features of most interest to the user of an induction motor are the speed, the torque, and the efficiency. Of importance to the user and the power company is the power factor.

In Fig. 412 the straight graph indicates synchronous speed. A synchronous motor runs at constant synchronous speed at all safe loads. The actual pull-out load may be 500% full load, but the motor shows signs of being unstable long before this overload is reached.

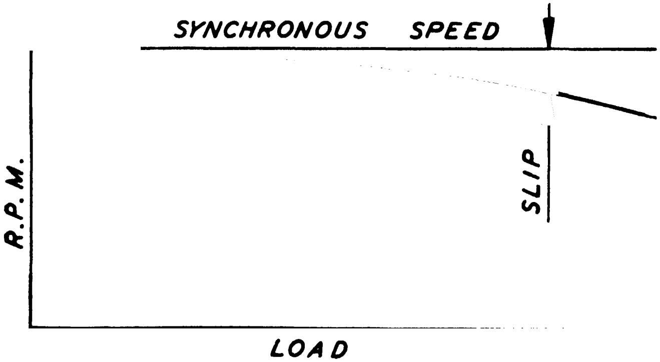


FIG. 412

A synchronous motor cannot adjust itself to the load by a change of slip since its speed must be synchronous. It does make the adjustment, however, by a shift of the rotor with respect to the revolving flux in the stator. Thus Fig. 413 shows the middle of the rotor *N* located exactly opposite stator conductor No. 1. Now the impressed E.M.F. and the stator counter-E.M.F. for the condition of no load have the relationship shown in the vector picture Fig. 414, and the resulting voltage is very nearly zero if the two voltages E_i and E_c are very approximately equal, which is the case when the synchronous motor floats on the line. Now as external load is put on the rotor, the latter tends momentarily to slow down. This means that the middle of the *N* pole tends to slip momentarily behind the flux lines with which it has been moving in

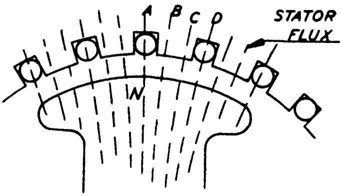


FIG. 413

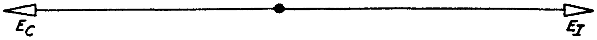


FIG. 414

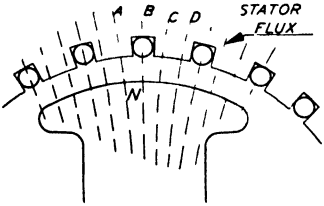


FIG. 415

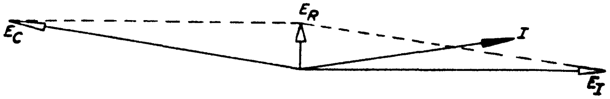


FIG. 416

synchronism. In other words the middle of the *N* pole slips behind flux line *A* to, let us say, the position of flux line *B*, in Fig. 415, between conductors 1 and 2. The *N* pole now revolves in synchronism with flux line *B*. And this means, too, that the counter E.M.F. has also correspondingly shifted back. Hence E_c and E_i now are related as shown in Fig. 416, and E_R is no longer zero. The current *I* now flows in the stator winding as a result of the load. Meantime the rotor which has slipped back from its original position by a very slight angle continues at constant synchronous speed.

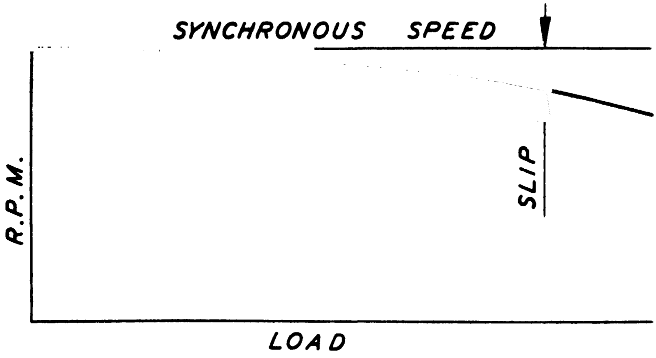


FIG. 417

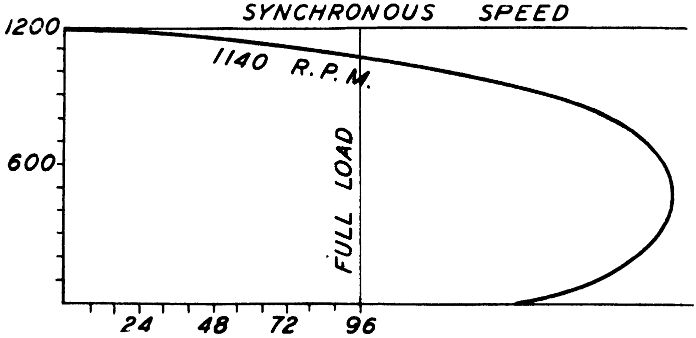


FIG. 418

The induction motor, as we have seen, carries its load by additional rotor current that results from slip. Fig. 417

shows this dropping off of the speed due to slip if the slip increased strictly in proportion to the load. But slip increases at a somewhat faster rate than the load because of magnetic and other changes in both stator and rotor. Hence the actual speed-torque characteristic of an induction motor is as shown in Fig. 418. The constancy of speed and the "break-down" or "pull-out" points are apparent. The latter occurs at about 250% full load. This graph is typical of

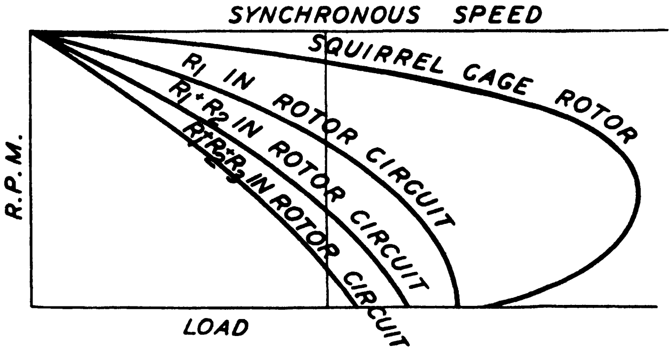


FIG. 419

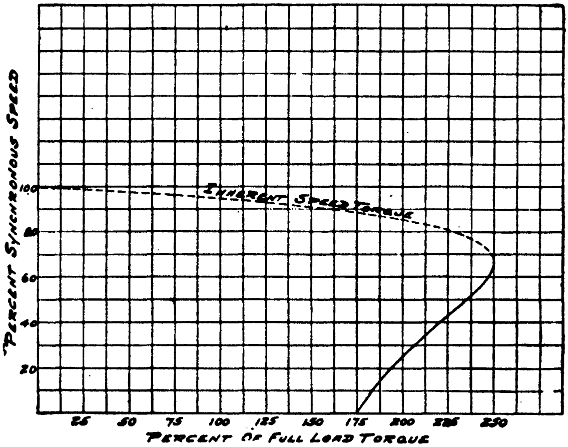


FIG. 420

squirrel-cage motor or of a wound-rotor motor with rotor short-circuited. As resistance in the rotor circuit is inserted the graph assumes the shapes shown in Fig. 419 depending upon how much external resistance happens to be inserted.

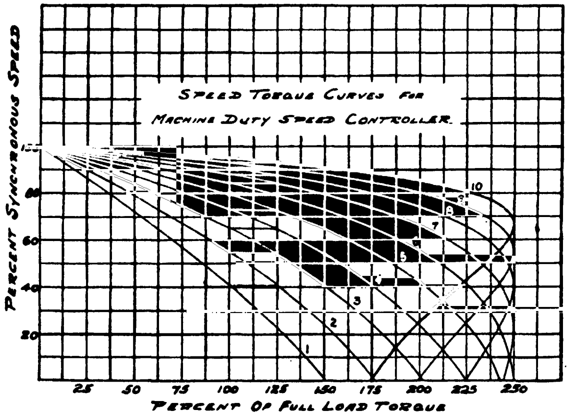


FIG. 421

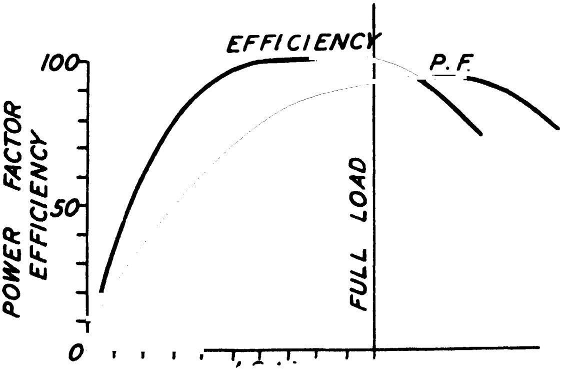


FIG. 422

The graphs in Figs. 420, 421 are for a Wagner slip-ring motor.

The current input into the stator consists of two parts: that which magnetizes the stator core, or exciting current, and the load current. The power factor of an induction motor is low when the load is zero or low, because the exciting current being fairly constant for all loads has a predominating influence on the line current while the load component is small. Since the magnetizing current lags by approximately 90°, the power factor is very low at low loads. As the load component of current increases due to greater load output, the magnetizing component is less significant and hence the power factor improves. This is shown by the graph in Fig. 422. This illustration also shows a graph of the efficiency of an induction motor. The losses in an induction motor are core or iron losses, stator copper loss, rotor copper loss, and friction and windage. Core losses and friction are fairly constant at all loads and speeds; the stator and rotor copper losses increase rapidly with load. The efficiency approaches its maximum near half-load and decreases slightly over a wide range beyond full load.

On the basis of the characteristics just described the squirrel-cage three-phase motor is well adapted for general constant speed service, because of its rugged construction, relative freedom from maintenance, and its reliability in operation. But its starting torque is relatively small, since it may develop only 150% torque while taking a starting-current of perhaps 500% full-load current. For light starting duty it is well fitted.

On the other hand, where the starting duty demands large torque, the slip-ring motor finds an application. The starting current and torque then are dependent upon the resistance which the operator inserts into the rotor circuit. Moreover, the slip-ring motor makes possible variable speeds when these are demanded.

The synchronous motor as we have seen gives exact synchronous speed at all loads. This gives it a field all its own, which, though limited, becomes more important when we consider the fact that the synchronous motor may be made to take a leading current. A resistance cut into the D.C. field winding of the synchronous motor allows variation of the field current over a wide range. When the field current is small the motor is said to be under-excited. For large field currents the motor is said to be over-excited. By means of this varying field current, it is possible to make the synchronous motor take either leading or lagging currents. Thus in Fig. 423, the graph shows that as the field current was varied the power factor at which it was operating changed from lagging, at low field current, to leading power factor for over-excitation. At normal excitation the power factor became approximately unity.

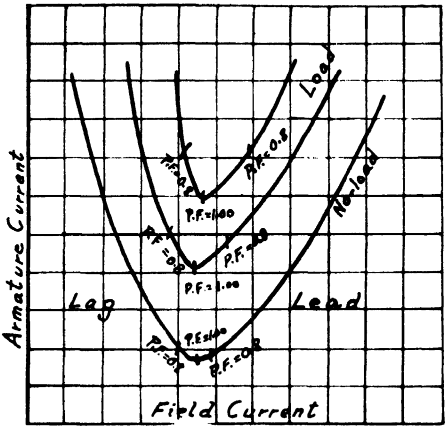


FIG. 423

Now this means that a synchronous motor aside from its constant speed characteristic can be used to correct bad lagging power factors of induction motors by being made to take a leading current. Hence where it is possible to use a constant-speed motor, as for pumps, for instance, it may be advisable to install a synchronous motor and use it as a means of improving the power factor of the whole plant. See also section 88.

73. THE FYNN-WEICHSEL MOTOR:

This motor is a sort of cross between the wound-rotor motor and the synchronous. The stator is very much like the induction motor stator, but there are two windings displaced at 90°. Fig. 424 shows the concentric stator coils and the 90° displacement of the two windings. At the moment of starting, resistance is inserted into both windings, the field winding proper and the auxiliary. Note, too (Fig. 425), that the windings are short-circuited during the starting-period. After reaching full speed, with all the resistance cut out, these windings are reconnected by switch action to conform to the running connections shown in Fig. 426. Observe that the

Fig. 424

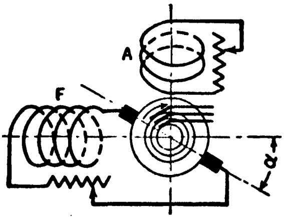


Fig. 425

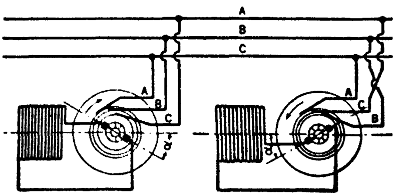


Fig. 426

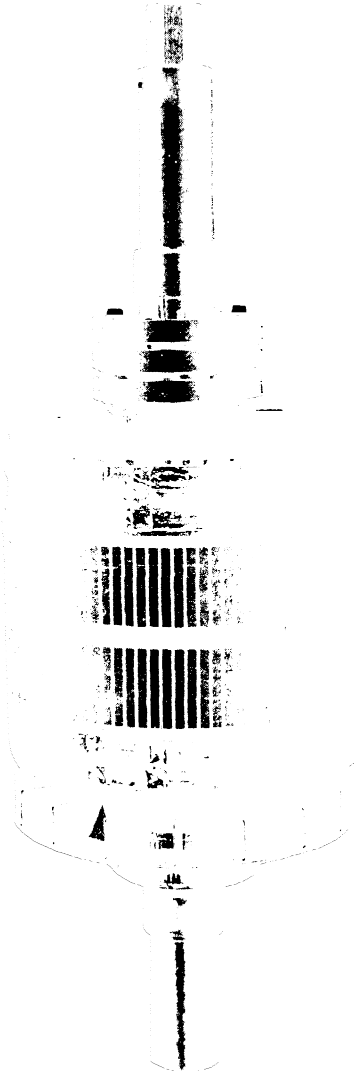


FIG. 427

field is now connected in series with the brushes on the commutator of the rotor. The brushes themselves are located at a position between the centers of the two windings.

The rotor of this motor (Fig. 427) has both slip rings and commutator. The rotor slots also have two windings: a small D.C. winding with leads connected to the commutator, and a standard polyphase slip-ring winding. The slip-rings are connected to the three-phase supply line. In this motor, therefore, the revolving field is in the rotor core, not the stator. The revolving flux cuts not only the two sets of stator conductors but also the conductors of the rotor D.C. winding.

The result of this peculiar arrangement is to give a motor that combines synchronous motor characteristics with slip-ring motor characteristics. The Fynn-Weichsel motor shows slip-ring starting characteristics with almost synchronous speed. Under ordinary load conditions and even with overload it runs as a synchronous motor taking leading current. With excessive overloads it pulls out of synchronism to run as an induction motor.

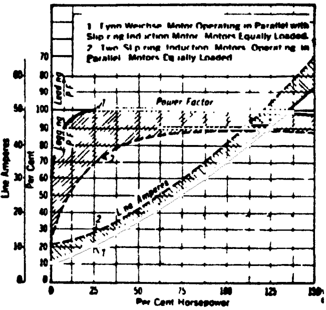
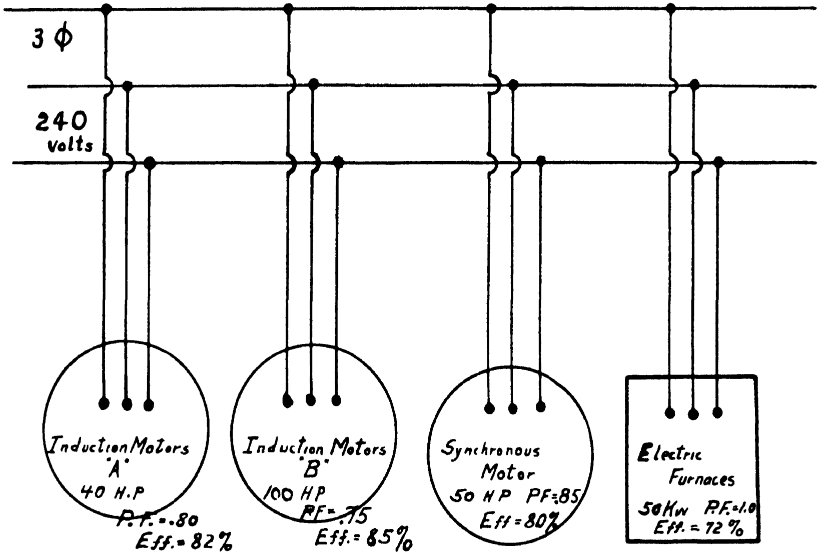


FIG. 428

Accordingly it has the desirable feature of correcting for bad power factor of other motors. Thus, Fig. 428 shows power factor graphs for two slip-ring motors together, and for one slip-ring motor used with a Fynn-Weichsel motor. The correction of power factor is quite obvious.

PROBLEMS—CHAPTER VII

1. A small shop uses three 5 H.P., two 10 H.P., two 25 H.P., and one 40 H.P., three-phase squirrel-cage motors. These motors are all rated for use at 240 volts and operate at 80% power factor at full load. If all are used at the same time, what is the total full load output of the motors?
2. If the motors in problem 1 operate at 85% efficiency, what is the total Kva. input at full load?
3. What is the main line current under the conditions existing in problem 2?
4. What is the phase angle in problems 2 and 3?
5. If a synchronous motor were added to the induction motors in this shop, what would have to be its current capacity at 90% power factor to bring the power factor of the main line up to unity?
6. What would be the approximate Kva. rating of this synchronous motor?
7. What is the synchronous speed of an 8-pole 60-cycle, three-phase induction motor?
8. What is the synchronous speed of an 8-pole 25-cycle induction motor?
9. The synchronous speed of a 6-pole induction motor on 60 cycles is 1,200 R.P.M. At full load its speed is 1,140 R.P.M. What is the slip in R.P.M.? What is the % slip?
10. Draw a graph which shows the conditions existing in problem 9. On the basis of this graph, what is the approximate slip at half load? At 75% load? At 25% overload?
11. An 8-pole and a 4-pole induction motor are connected in cascade. What are the four speeds possible with this combination?
12. What power output is possible through the use of the two motors in cascade?
13. Refer to Appendix Tables. Determine the starting fuse capacity and the running fuse capacity of a 5 H.P., 220-volt, squirrel-cage, 3-phase induction motor? A 25 H.P. motor?
14. What are the full load amperes listed in the Appendix Tables for the following:
    a) 40 H.P. 3-phase squirrel cage motor.
    b) 100 H.P. 3-phase squirrel cage motor.
    c) 40 H.P. 3-phase wound rotor motor.
    d) 100 H.P. 3-phase wound rotor motor.



15. The average power loads in a certain factory are as shown in the accompanying diagram. Determine the following:
   - a) Kva. input into induction motors *A*.
   - b) Kva. input into induction motors *B*.
   - c) Kva. input into furnaces.
   - d) Kva. input into synchronous motor.
   - e) Total Kva. input into feeder lines.
   - f) Main line current.
   - g) Power factor of system.
   - h) Overall efficiency of system.
   - i) Current in each (low-voltage) phase of the transformer.

CHAPTER VIII

A.C. MOTOR STARTING DEVICES

74. NATIONAL CODE AND LOCAL REGULATIONS:

Regardless of the size of a motor, some provision must be made for starting and stopping it conveniently and safely. The National Electrical Code and local regulations specify the kind of device to be used according to the size of the motor or the nature of the installation. Some communities follow the regulations of the National Underwriters' Electrical Code, others supplement the Code rules by local regulations which are more rigid.

In the city of Detroit, the local rules, for example, permit single-phase motors of ½ H.P. or less to be connected to the 110-volt lines. Motors of larger capacity than ½ H.P. must be connected to 220-volt lines or the power lines. Similarly, local rules in Detroit require that single-phase motors above 3 H.P. capacity, must be equipped with a resistance type of starter. Single-phase motors having a capacity of more than 15 H.P. are not permitted in Detroit, except by special permission.

In accordance with regulations such as these, various kinds of starting-devices and control devices must be connected in a motor circuit to insure safety and convenience, each community being the judge as to how this is best accomplished. Thus, according to the above regulations (Detroit) single-phase motors of ½ H.P. or less may be operated by means of a two-pole switch or even a single-pole switch. This switch could be of the flush, surface, or knife-blade type, and need not be fused if fuses are provided in the distribution panel from which the motor is being fed.

75. SINGLE-PHASE MOTOR STARTERS (MANUAL):

Single phase motors operating on 220 volts require, in most instances, line switches different from those running on 110-volt lines. The reason for this is the higher voltage as well as the fact that such motors are more likely to be above the ½ H.P. size. In Detroit, where a starting rheostat must be used with motors above 3 H.P. capacity, those up to and including this size may be started by line switches. There are, of course, many different switches from which to make a selection. Thus the tumbler switch in Fig. 429, specially designed for motor operation, may be used for smaller motors. If the motor has fuse or other overload protection at the distribution panel, or at some other convenient location, no

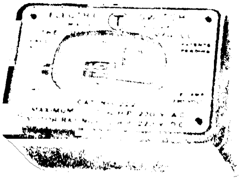


Fig. 429

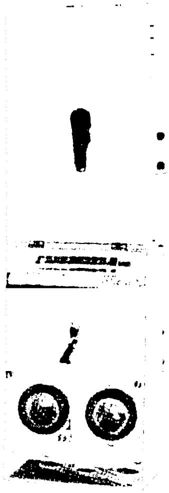


Fig. 430

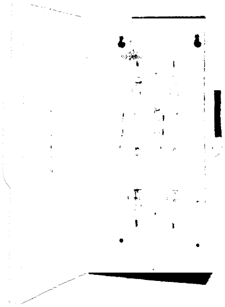


Fig. 431

other protection is needed at the switch. Tumbler switches with fuse protection (Fig. 430), may be used to good advantage where the fuse panel is too far removed from the motor. The motor switch need not confine itself to the tumbler type. It may be an inclosed, fused knife switch (Fig. 431), or again it may be an inclosed knife or contactor type of switch having thermal cutout or thermal relay overload protection. Some of these switches are made only in the smaller current capacities, while others are made to carry large amounts of current. Therefore, the selection of a switch for a particular single-phase motor will depend on the size of the motor and the kind of overload protection desired.

Single-phase motors over 3 H.P. must have in addition to the switch a starting rheostat. This starter is similar in appearance to those used for direct current motors. Each has resistance elements, a release magnet, a set of contacts, and a lever arm with a contact finger. There is, however, sufficient difference between the two to confine each to its particular field of use. In the smaller-size starting rheostat (Fig. 432), the resistance element consists of a resistance wire wound on a round or oval insulator (Fig. 433). The number of elements in a rheostat depends on the size of the motor and the voltage. The resistance element in the larger-size rheostats consists of a number of alloy or cast iron grids

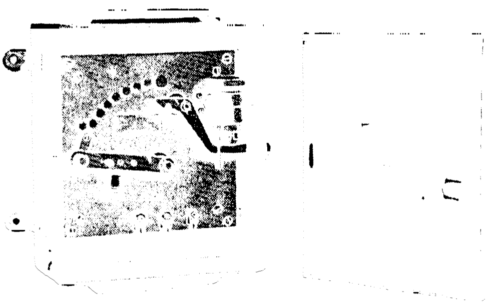


Fig. 432

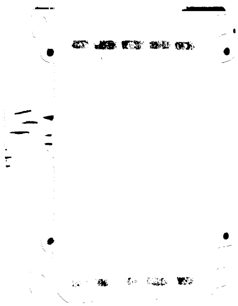


Fig. 433

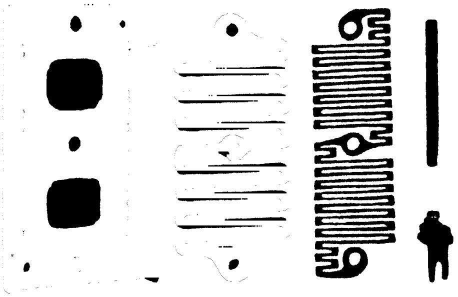


Fig. 434

(Fig. 434), which are assembled together as in Fig. 435 to give the necessary resistance for a given size machine. At various intervals taps are brought out, which are connected to the contact points of the panel board. The lever passing from contact to contact cuts the resistance out of the circuit as the motor accelerates its speed until full speed is reached, when the motor is connected directly across the line. The main resistance that makes up the rheostat (see Fig. 436)

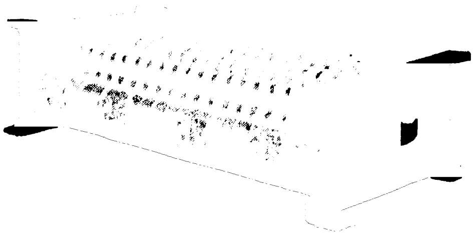


FIG. 435

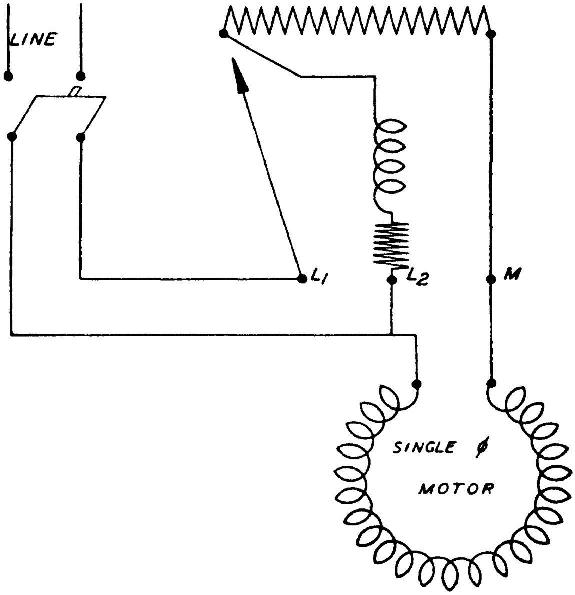


FIG. 436

is always connected in series (Fig. 436) with the primary (stator) winding of the motor. In addition to the main resistance, there is usually a single high resistance element which has no direct bearing on the starting-current, and which is connected in series with the winding of the release magnet. Ordinarily the resistance of the winding on the release magnet is so low that if it were connected directly across the line it would burn up in a short time. To reduce the current through the magnet to keep it from burning up and to lower the cost of operation to a minimum, this extra resistance element is used with the magnet. The release magnet has a definite function to perform, viz., to stop the flow of current to the motor by releasing the lever to the "off" position, when the voltage drops below a reasonable value, or when the line is opened. When the voltage comes back to normal, the motor must be restarted.

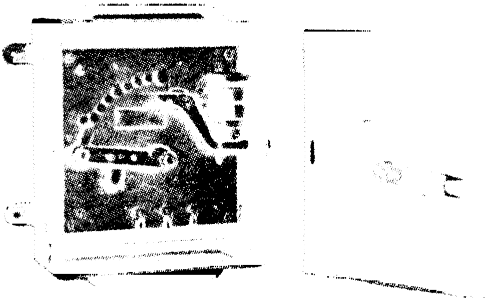


FIG. 437

The core of a direct current release magnet is usually made of solid cast iron, or soft steel, and attracts a small rectangular piece of iron (called the armature) loosely pivoted to the lever arm. The winding of the alternating current release magnet is ordinarily placed on a thin brass tubing. A core made of laminated sheet iron or steel is placed within the brass tubing and is free to move parallel to it. When a current flows through the winding, the core is pulled up into the brass tubing and held there until the current is shut off. The magnet is so placed on the panel that when the current is shut off, the force of gravity causes the core to drop on the free end of the holding arm (see Fig. 437), which in turn releases the contact-making lever, permitting the lever to drop from the "running" to the "off" position.

76. THREE-PHASE MOTOR STARTERS (MANUAL):

The starting-current of some three-phase motors is comparatively high, running in the neighborhood of 800 to 1,000% of the normal full-load current. The fact that the starting-current is high naturally presents a serious problem.

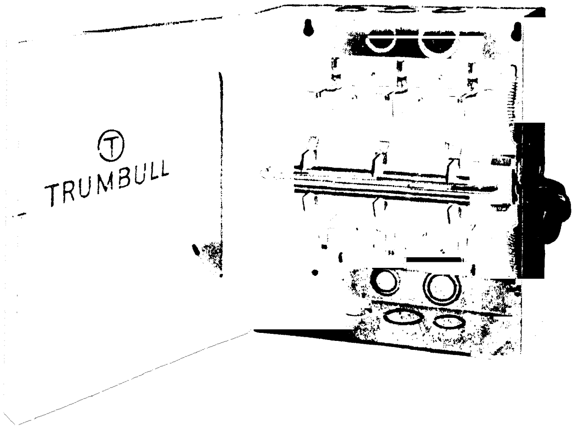


FIG. 438

The seriousness arises from the interference set up in the power lines and the equipment connected to them during the starting-period of the larger-size motors. The Code requires that the starting-current of a three-phase motor must not exceed 250% of the full-load running-current. This might at first appear as increasing the difficulty. On the contrary it presented a measure of something definite toward which to work, and the result is that today there are numerous kinds of starting devices.

The size of a motor determines to a large measure the kind of starter to be used. The National Code does not set definite limits on polyphase starting contrivances. Therefore local regulations should be considered before making an installation. Let us consider several kinds of three-phase starting devices.

a) The Three-Phase Motor Starting-Switch: The smaller size motors, usually up to and including the 15 H.P., use the simpler type of three-phase starting appliances. Among these there is the three-phase motor starting-switch. It is a three-pole, double-throw switch, having one side fused. See Figs.

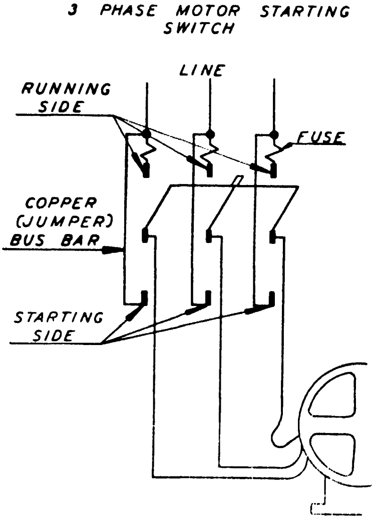


FIG. 439

438, 439. When starting a motor with this switch, the blades are thrown to the unfused side, often referred to as the starting-side. The current passes from the main line directly to the motor. When the motor approaches full speed, the switch blades are quickly thrown from the unfused side to the fused side of the switch, also known as the running-side. The motor is now protected against excessive overload by the fuses. The switch is so arranged that the blades cannot remain in the starting position, when the switch handle is released. An insulated bar mounted on springs is placed across the clips of the switch on the starting-side. The springs are strong enough to force the blades out from the clips when the pressure on the handle is removed. The time required for "throwing over" should be as short as possible so as not to allow the motor to decelerate too much; otherwise, the running fuses might "blow."

In mounting the switch, it should be placed horizontally, or, when such an installation is inconvenient for operation, the switch should be placed with the running-side up and the starting-side down. Even though the force of gravity might cause the blades to drop down, they could only fall on the insulated bar and would not come into contact with the switch clips of the starting-side.

In addition to the motor starting-switch just described, there is another whose principle is the same, but which differs in construction and operation. This switch (Fig. 440) is of a later design and instead of being a double-throw switch, it is single-throw. This switch has two sets of blades as well as clips. One set closes the circuit between the line leads and the motor fuses. The other set is in parallel with the motor fuses (short-circuits the fuses). To operate the switch, the handle is thrown one way only, as in the case of an ordinary single-throw switch except that pressure must be maintained on the handle until the motor has attained full speed. When the handle is pushed forward to close the switch, both sets of switch blades operate except that the blades in parallel with the fuses close sooner than the blades in series with the fuses.

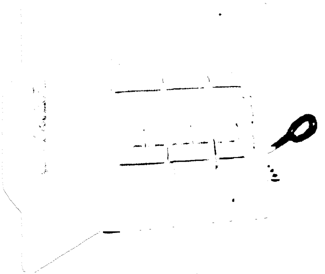


FIG. 440

When both sets of switch blades are closed, the current flows from the line through the switch blades closing the circuit, then through the switch blades in parallel with the fuses, and finally through the leads to the motor. A small portion of the current passes through the motor fuses, during the starting-period, but the amount is small, due to the difference in resistance between the switch blade and the fuse link. If the fuses were not protected by the switch blades during the starting-period, the large starting-current would cause them

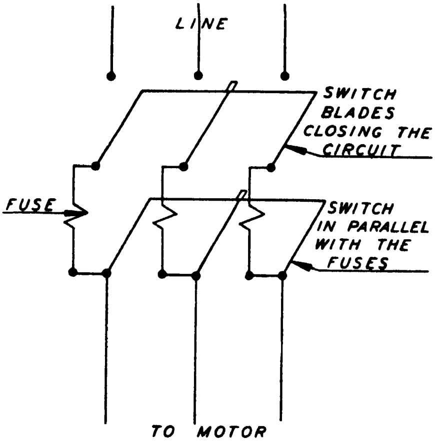

LINE
SWITCH BLADES CLOSING THE CIRCUIT
FUSE
SWITCH IN PARALLEL WITH THE FUSES
TO MOTOR

Fig. 441

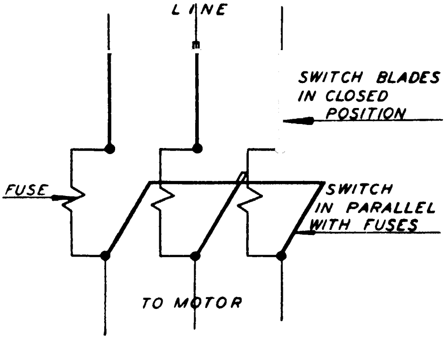

LINE
SWITCH BLADES IN CLOSED POSITION
FUSE
SWITCH IN PARALLEL WITH FUSES
TO MOTOR

Fig. 442

to blow. Therefore, the hand should push the lever until the motor reaches full speed. See Figs. 441, 442. When the hand is removed, the lever returns a short distance and the switch blades in parallel with the fuses are disconnected, permitting the current to pass from the line, through the fuses, to the motor. The motor is now protected against excessive overload by the fuses. The other set of switch blades remains in the circuit until the switch is opened by pulling the lever, which of course, disconnects the line wires and causes the motor to stop.

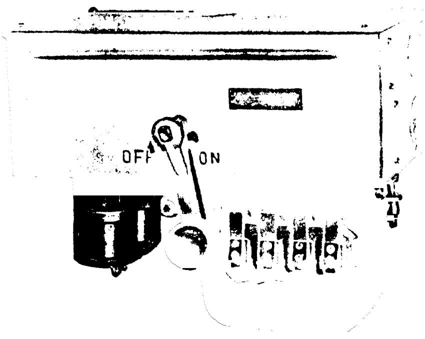


FIG. 443

b) Three-Phase Oil Switch: A switch that finds much favor as a starting-switch for any kind of alternating current motor operating up to 600 volts is the oil switch (Fig. 443). It is quite different in construction and operation from the switches previously mentioned. In the first place the circuit "make" and "break" mechanism is immersed in oil. This mechanism may consist of a set of switch blades and jaws, or it may consist of a set of contacts and contact fingers. The switch blades or contact fingers are operated by a handle placed on the outside of the metal case, inclosing all the parts of the switch. The handle has only two positions: "on" and "off." When it is thrown to the "on" position, the handle need not be held there until the motor attains full speed and then released. In this respect the switch operates just like an ordinary switch for closing a circuit. To open the switch the handle is thrown from the "on" to the "off" position. This switch does not include fuse protection against excessive overload and large starting-current. It is, however, equipped with an overload trip, which is controlled by a time-limiting device. When the current passing to the motor is above normal, the overload release comes into action, tripping the handle and opening the switch. However, the release mechanism does not operate instantaneously, but only after a short-time interval. The period of time that elapses before tripping can be varied by adjustment. There are times when excessive current flows only for a few seconds and then drops back to normal value. Thus a cutting tool may encounter occasional "hard" spots in metal being machined, which would put additional load on the driving motor. It is not always convenient to have the circuit opened every time the current exceeds a definite value. On the other hand should the current remain above normal longer than advisable, the switch should be opened. That is exactly what happens with this type of switch. During the starting-period the current is far above normal for a period of time, seldom exceeding a few seconds and drops rapidly to normal. If the time-limiting device is set for operation after twenty seconds or so, the starting-current can pass without any interference on the part of the switch.

The time-limiting device consists of one or more cylinders ("dash pots") in which a plunger or piston moves. This piston is provided with a small hole, the size of which can be varied, as a means of regulating the speed of the piston. The larger the opening, the faster the piston moves. In some "dash pots," the piston is required to move against a resistance of oil, while in others it acts against air. If oil is used, it must be of a particular kind, made specially for this purpose.

The connections of this switch for a three-phase motor are simple. There are three terminals for the line wires and three for the motor leads.

c) The Star-Delta Switch: When a three-phase motor with a normal delta-connected winding has both leads from each phase brought out to a terminal block or through a fitting,

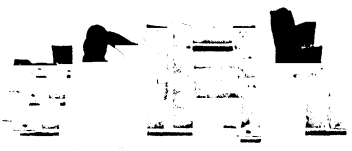


Fig. 444

a switch known as the star-delta switch (Fig. 444), may be used in place of a starting-switch. Of course such an installation is more costly, due to the need of two switches: the

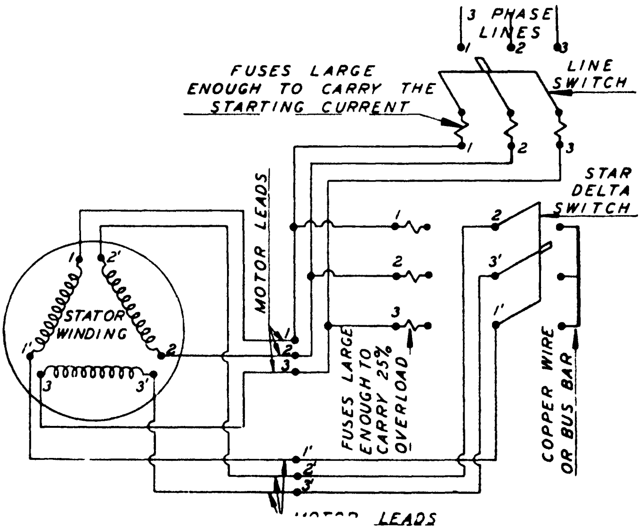


Fig. 445

one a line switch for disconnecting the feed line; the other, a star-delta switch for starting purposes. However, such an installation may compensate for itself in localities where it can be used on motors over 15 H.P. Otherwise a compensator or auto-starter must be used, which is still more costly.

Ordinarily the leads from the different phases are not brought outside of the motor by the manufacturer. If use of a star-delta switch is contemplated it is necessary to include such specifications when purchasing a motor, or to make the changes on a standard motor after it is purchased.

A casual observation of the star-delta switch might give the impression that it is the same as the so-called motor starting-switch. A closer analysis will reveal that the connections here are quite different. These connections are shown in the wiring diagram (Fig. 445). The operation of the star-delta switch is the same as the double-throw motor starting-switch. The switch blades are first thrown to the starting-side and held there until the motor comes up to full speed and then the switch blades are quickly thrown to the running-side.

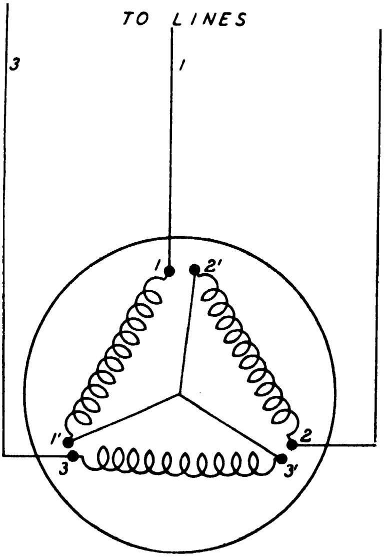


FIG. 446

The connection of the switch is more difficult than any of the motor starting-switches taken up so far. Tracing from the line (Fig. 445), the connections for a three-phase motor are as follows: The line wires feed to a three-pole, single-throw fused switch. From this switch the three wires pass directly to one lead of each phase (*A-B-C*) of the motor. Also the wires are tapped and connections are made to the fused terminals of the star-delta switch (1-2-3) as shown in the wiring diagram. Connection is made between each switch blade and the remaining phase leads, as illustrated in the wiring diagram. Note that the switch blades are marked from the top 2′, 3′, 1′, and the phase leads 1′, 2′, 3′, must be connected to the switch blade having the corresponding number, in order that each phase may be connected across two line wires of the three-phase when the delta connection is made. The switch jaws on the starting side of the switch are all connected together with a wire or bus bar. When the switch blades make contact with the jaws of the starting-side, the winding of the motor is arranged in a star connection. When the switch blades are thrown to the running-side, the star connection is broken and the motor winding is connected in delta as shown in the two illustrations (Figs. 446, 447).

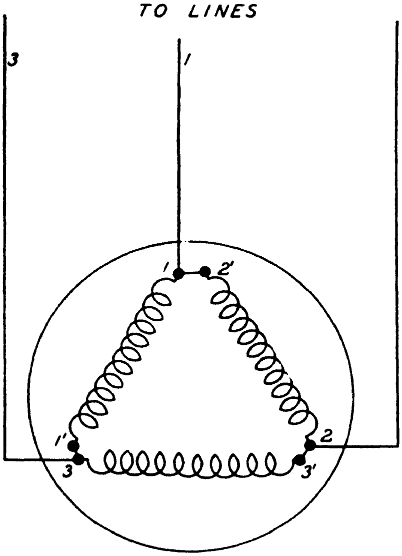


FIG. 447

By connecting the delta winding of the motor in star during the starting-period, the normal line voltage is reduced to about 58% for each phase, and the starting-line current is reduced to about 33% of the current that would be taken if the motor were connected in delta directly across the line.

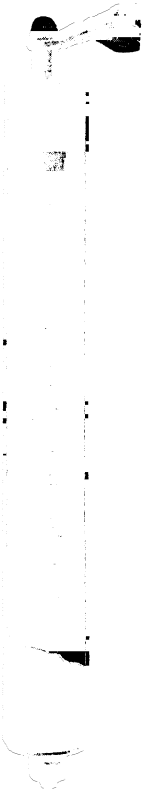


FIG. 448

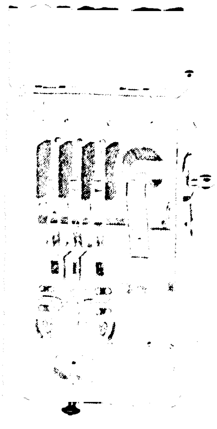


FIG. 449

d) Resistance-Type Starter: This type of starter uses a resistance as a means of reducing the current to the motor during the starting-period. The resistance element may consist of resistance wire or of graphite disks assembled in a steel tube (Fig. 448), which has an insulated inner lining. In either case the purpose is to "cut in" the resistance into the circuit until the motor comes up to full speed. The one type does this by means of contacts, which cut the resistance into the circuit at the start and short-circuit it out of the circuit when the motor is up to speed. The carbon-disk type accomplishes the same result by slowly compressing the disks of the resistance elements until the motor comes to full speed, when the resistance is "shorted" out of the circuit. In order that the current flowing in each line to the motor may be of the same value, the elements in each line must be of the same resistance. Hence the graphite disks must be compressed equally.

Fig. 449 shows a resistance-type starter using resistance-wire elements. Fig. 450 shows a wiring diagram of this starter connected to the motor, and Fig. 450A shows the connections of the graphite type of starter. With this resistance-type starter, the voltage is reduced to about 82% with an approximate starting-torque of 65%. To operate this starter the handle is thrown to a position marked "start," and is held there until the motor comes up to full speed. The handle is then released and permitted to fall into the running-position. This starter is usually equipped with a "thermal overload" release and an "undervoltage" release. The thermal

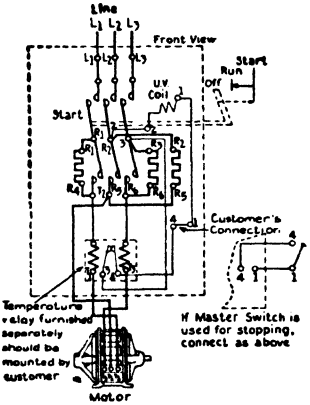

Line
L1 L2 L3
Front View
L1 L2 L3
Start
Run
Off
U.V. Coil
1
Start
2
R1
R1
R2
3
R3
R2
R4
T2
R5
R6
R6
R5
4
1
Customer's Connection
4
4
1
1
3
3
4
Temperature relay furnished separately should be mounted by customer
If Master Switch is used for stopping, connect as above
Motor

FIG. 450

overload release consists of a heating coil, through which the current to the motor passes. The heat of the coil causes a piece of thermostatic metal to be deflected which in turn causes a set of contacts to open and to disconnect the line. The release has an arrangement whereby the amount of overload can be adjusted. The undervoltage release is usually an electromagnet which weakens sufficiently to allow the arm to drop back when the voltage drops below a required value.

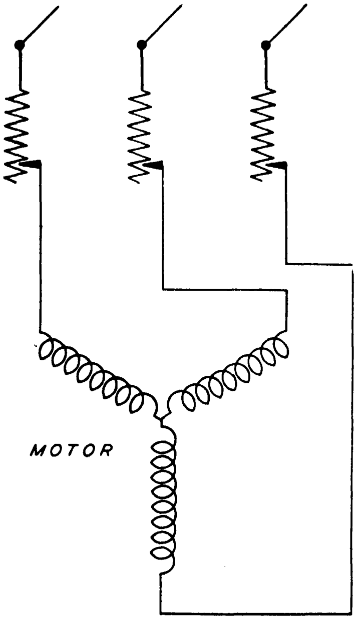


Fig. 450A

In either case when a release opens the circuit, the motor must be restarted.

Fig. 451 shows graphite resistors mounted in a starter and Fig. 452 shows the front view of an assembled starter. It is operated by moving the lever on the outside of the steel cabinet slowly upward. The graphite disks are slowly compressed, thereby gradually lowering the resistance, and the motor accelerates in speed. When the motor has attained full speed the resistances are "shorted" out of the circuit, and the motor is connected directly across the line. For protecting the motor, the starter is equipped with overload and under-voltage coils. The overload protection consists of a magnet

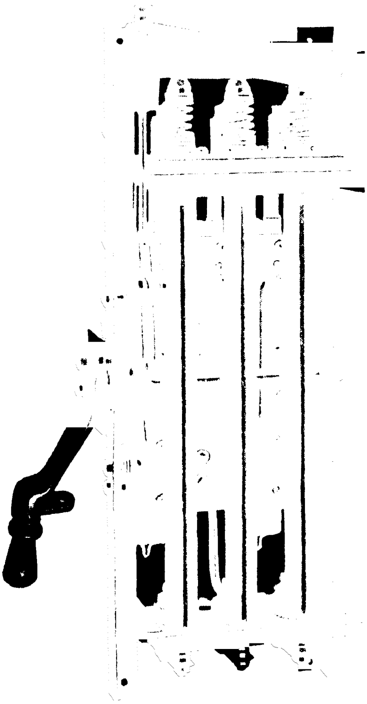


FIG. 451

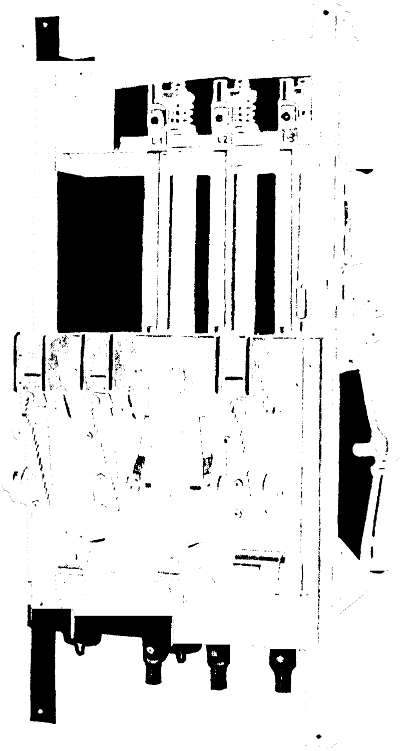


FIG. 452

which can be regulated to permit only a limited amount of current to flow. When the current is in excess of the value allowed by the coil, the magnetism set up is sufficient to pull a plunger, which in turn trips the contacts, thus opening the line wires and stopping the motor. In order that the movement of the plunger may not be too rapid, a dash pot is attached to it. The overload release magnet is connected in series with the line feeding the motor. For three-phase motors, two magnets are required, one in each of two line wires. Two are also needed for two-phase motors whether three or four wires are used.

"No-voltage" protection is afforded by means of a small high resistance magnet connected across two of the three wires. When the voltage drops too low or is shut off entirely, the magnet causes the line contacts to be opened. The resistance type of starter adapts itself for starting use with motors, where the starting duty is not too heavy, otherwise compensator starters should be used.

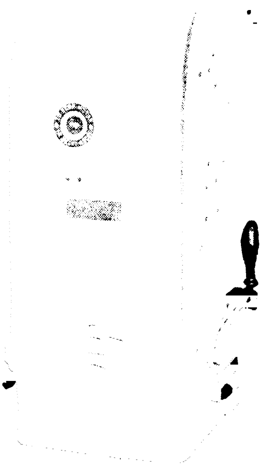


FIG. 453

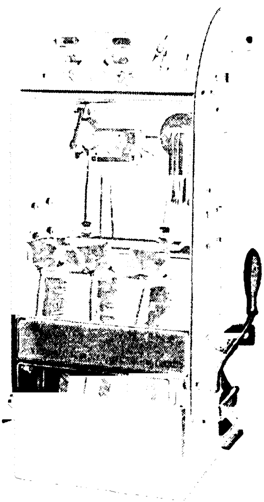


FIG. 454

e) The Compensator Starter: Motors over 15 H.P. ordinarily require a compensator (Figs. 453, 454) for starting, although some motors may still come within the range of the star-delta switch or the resistance type of starter. Briefly, the compensator, or auto-starter as it is often called, consists of a transformer and a set of contacts and contact-makers, usually immersed in oil. The contacts are so arranged that some make contact during the starting-period, while others make contact during the running-period of the motor.

The transformer as here used differs from the ordinary power transformer in that it has only one coil which serves

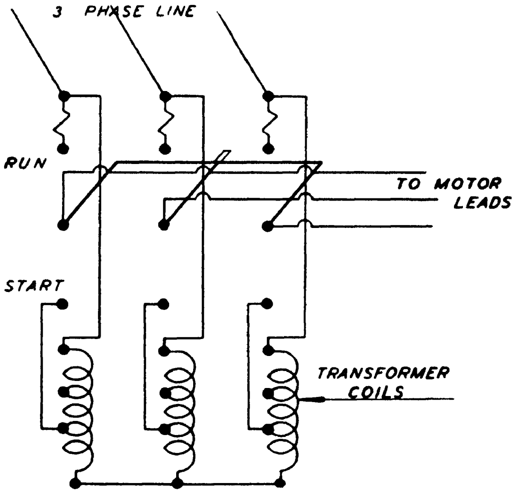


FIG. 455

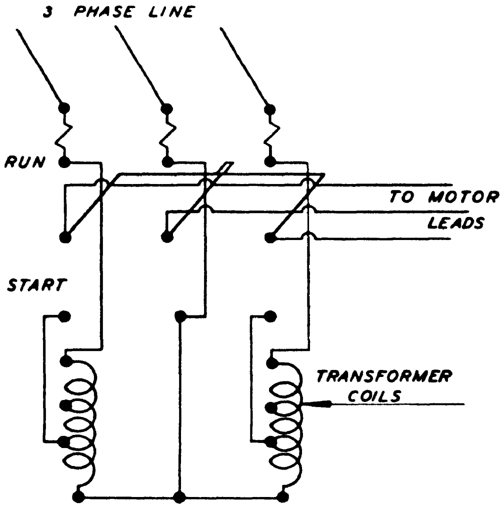


FIG. 455A

for both primary and secondary. The connections are shown in Figs. 455 and 455A. The transformer coil is connected directly across the supply line wires. The leads from the motor are connected to the switch blades, which, when thrown downward to the starting-position connect the motor to the 50%, 65% or 80% taps as desired. Two or three taps are usually available. The line is connected to the switch clips at the top (running-side) and also directly to the transformer coils. The three transformer coils are connected in star. Either a two- or a three-coil compensator may be used for both two- and three-phase motors.

The general construction of the compensator (three-phase), which has already been suggested in Fig. 454, is further illustrated by the succeeding wiring diagrams. When the blades are pushed down to engage the starting contacts two connections are completed: first the line wires are directly connected to the "finish" ends of the auto-transformer coils; and second, the taps taken on these coils are connected (through an overload relay device) directly to the three motor terminals (see Fig. 456). Observe that the "start" ends of the three auto-transformer coils are connected together to form a neu-

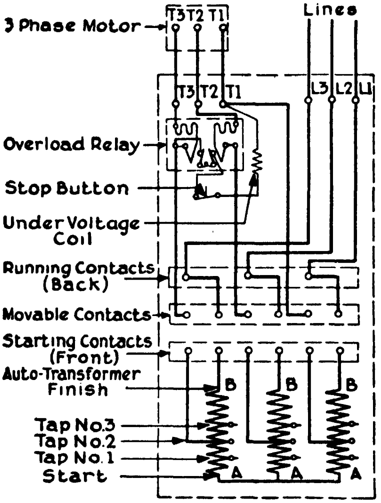


FIG. 456

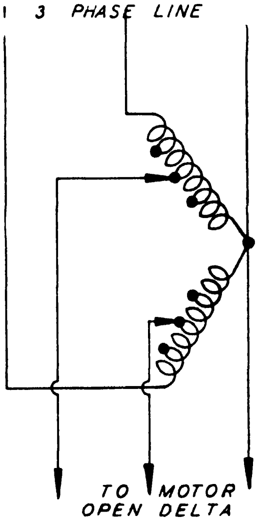
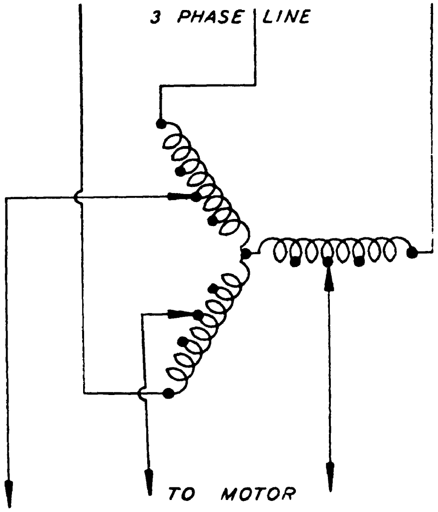


FIG. 457

tral point, thus arranging the three coils definitely as a three-phase star. Observe also that in the diagram, three possible taps are shown for the particular compensator illustrated.

The transformer of a three-phase compensator may consist of two or three coils or windings. Some manufactures use two coils, others use three coils. When two coils are used, they are in open delta Fig. 457. When three coils are used, they are connected in star as shown in Fig. 458. Either type may be used for a star or a delta-connected stator winding of a three-phase motor.



STAR

FIG. 458

The compensator coils are mounted on a core built up of laminated iron or soft steel. Each coil consists of a single winding with taps taken at different intervals to get various starting-current values. Ordinarily taps are placed to give 50, 65, or 80% of the coil voltage. Each phase of the motor has impressed on it, therefore, 50%, 65%, or 80% of the line voltage according as we have chosen one or the other of the given taps. This makes the current input into the motor 50%, 65%, or 80% of what it would be if the line voltage were directly impressed on the motor. The line current, however, is only half of the motor current, hence it would be for the different taps 25%, 42%, or 64% as large as if the motor were thrown directly across the line. Fig. 459 will help to make this clear and will explain further the action of the auto-transformer.

All of the parts that make up the compensator are inclosed in a metal case, which is constructed to permit easy access to any part. A handle for operating the contacts is placed on the outside of the cabinet. This handle is pulled forward during the starting period and held there, until the motor reaches full speed, when it is quickly pushed backward to the running position. The mechanism of the compensator does not allow the contacts to remain in the starting position, nor can the handle be pushed into the running position, without first being brought to the starting position. A magnet which is connected across two of the line wires of the three-phase line holds the handle in the running position. This magnet also acts as a no-voltage or under-voltage release. As soon as the voltage drops below a reasonable value or is cut off entirely, the magnet loses its holding effect and the handle is released, falling to the "off" position and opening the line wires to the motor.

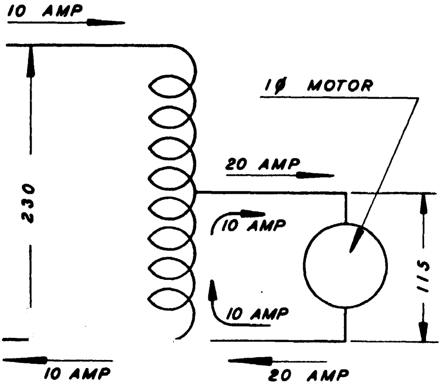


FIG. 459

Some compensators are equipped with nine leads (three line, three fuse, three motor) and others of later design have six leads (three line, three motor). The starter with nine leads does not have an overload protective device installed as part of the compensator. Hence the installation requires an additional fused switch placed directly above the compensator. The switch made for this particular purpose is known as a compensator switch. See Fig. 460.

The connection is shown in Fig. 461. The three-phase feeder lines connect to the switch jaws or clips. The leads marked "line" are connected to terminals of the switch blades and the compensator leads marked "fuse" are connected to the fuse clips of the switch. The switch must be closed before closing the starting contacts of the compensator. To stop a motor the switch should be opened, after which the compensator opens automatically.

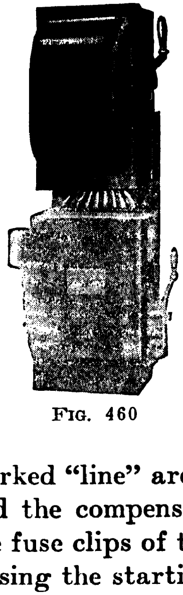


FIG. 460

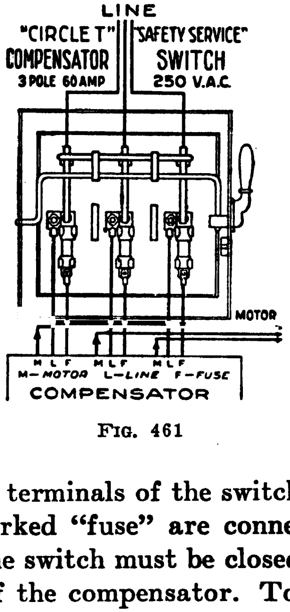


FIG. 461

The type of compensator which has three-line leads and three-motor leads has an overload protective device built in as part of the compensator. The device may be in the form of two magnets, respectively in series with two wires of the three-phase line, or it may be a thermal relay or release placed in two line wires of the three-phase system. When an overload protective device is part of the compensator, no compensator switch is needed. However, an ordinary three-pole, inclosed knife switch should be installed to shut off the current to the compensator when it is not in use or when repairs or adjustments on the starter are necessary. The connection of the three-pole switch is very simple. The three line wires are brought to the clips or jaws of the three-pole switch, and the three blades are then joined to the compensator terminals marked "line."

77. SPEED REGULATING RHEOSTATS FOR THREE-PHASE SLIP-RING TYPE MOTORS:

The speed-controlling rheostat (Fig. 462) is used in conjunction with the three-phase, wound rotor, induction motor, often called the slip-ring induction motor. The rheostat is not made for starting duty, rather it is designed to vary the induced current in the rotor and thereby control the speed. The speed of a motor may be reduced from full load speed to about 50% below full load speed. The resistance elements for the small-size regulator are made out of resistance-wire wound on insulators. The large regulators use resistance grids. The rheostat has three separate and distinct resistance units, each of which is connected to its own group of contacts. A common "star" connection is provided through three lever arms, which are connected together mechanically and electrically and operate simultaneously. When the levers are moved, each travels the same distance and each

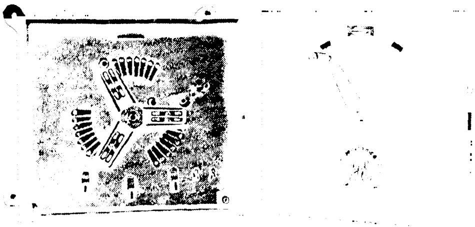


FIG. 462

one cuts "out" or "in" the same amount of resistance in its circuit. The construction is such that the lever arms may be left on any contact for any length of time. The capacity of the resistance elements in each circuit or phase is sufficient to prevent overheating.

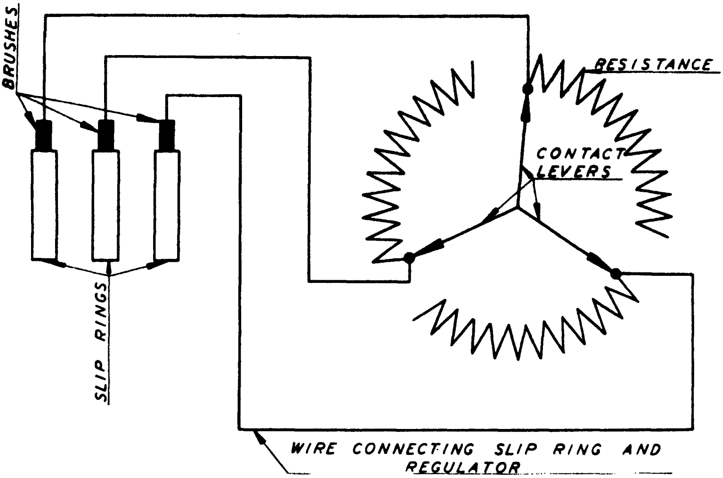


FIG. 463

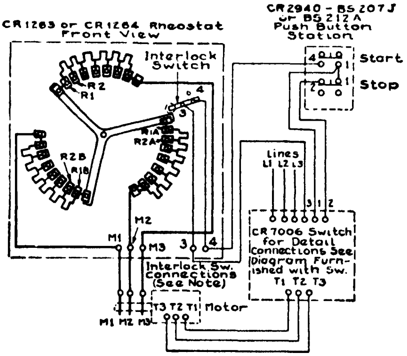

CR 1263 or CR 1264 Rheostat Front View
CR 2940 - BS 207 J or BS 212 A Push Button Station
Interlock Switch
Start
Stop
R2
R1
R1A
R2A
R2B
R1B
Lines
L1 L2 L3
3 1 2
M1
M2
M3
3
4
CR 7006 Switch for Detail Connections See Diagram Furnished with Sw.
T1 T2 T3
Interlock Sw. Connections (See Note)
T3 T2 T1 Motor
M1 M2 M3

FIG. 464

The connection of the rheostat is quite simple. The rotor is equipped with slip rings, one for each phase of the rotor winding. A metal or carbon brush makes contact with each slip ring. The connection consists in joining each brush to one of the resistance units of the rheostat as shown in Figs. 463, 464.

78. MAGNETIC SWITCHES AND AUTOMATIC STARTERS:

Starting devices for motors are not confined to the manually operated type. By the use of magnetic switches and automatic starters, motors can be started and stopped with the aid of the proper kind of push button control from one or from several convenient locations. The push buttons may be manually operated, or again they may be automatic in their operation. In the latter case they depend upon some mechanical or electrical device which determines the functioning of the push button. Automatic operation of electrical equipment is very much in evidence today in the home, the store, and the factory. Thus the temperature in an electric refrigerator determines the starting and the stopping of the motor that operates the cooling system. In very much the same way the temperature in a room determines the starting or the stopping of the motor which controls the drafts on the furnace. Turning "on" the valve on a fire hose feed pipe automatically starts the high pressure water pumps operating in large buildings. All of these are examples of automatically controlled motors. Manually operated push button stations are much in use on the individually driven machines of the modern factory.

It is not necessary that the large power wires feeding the motors be run to all the push buttons, because such push button stations require only wires of small current carrying capacity. The cost of such an installation is not great, but the convenience and the factor of safety are greatly increased. This is of particular importance where electrical machines are controlled by persons who have a meagre knowledge of electrical apparatus. The push button is, of course, used in conjunction with some form of magnetic switch. Its connections can best be given after a discussion of this type of switch.

For the controlling of small motors, where the Code does not specify particular starting equipment, magnetic switches of the proper number of poles and capacity may be used. Ordinarily a magnetic switch, or contactor as it is often called, consists of an electromagnet, an armature, and one or more contact points or fingers fastened to the armature by means of insulated bars or rods. The method of fastening the contact points or fingers varies with different manufacturers. See Figs. 465, 466. Usually the smaller switches use contact points, while the larger are equipped with contacts and contact fingers. Whether the switch is one for controlling the current to a motor on a small refrigerator or oil burner or for operating large motors, the principle under which the switch operates is the same. The closing of a push button

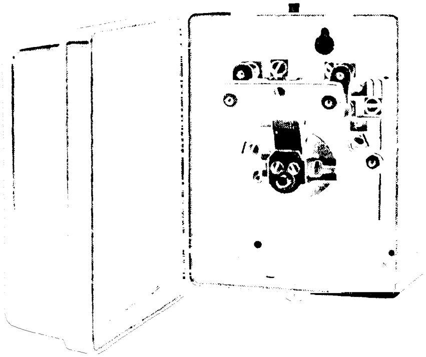


FIG. 465

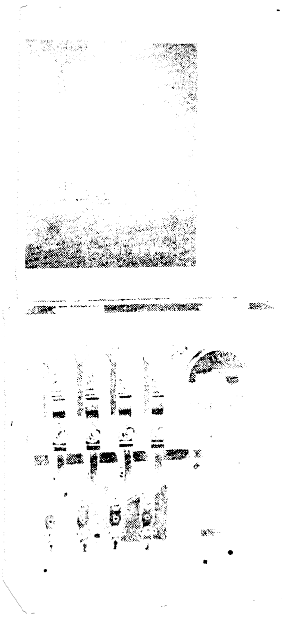


FIG. 466

circuit (Figs. 467 and 468), the closing of a circuit due to the falling or rising of a float switch, or the action of a thermostatic switch or pressure governor (Fig. 469) causes current to flow through the winding of the electromagnet.

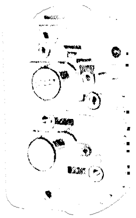


FIG. 467

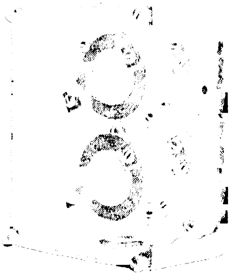


FIG. 468

The latter becoming energized, exerts a pull on the iron or steel yoke or armature. The contacts being mounted on this yoke, move as it moves, and thus close the motor circuit. A small spring, used as part of the contact assembly (Fig. 470), assures good electrical connection. So long as the electromagnet is alive, the yoke and the contacts are held in the "closed" position. When the current is shut off, the magnet loses its hold. The force of gravity acting on the armature and assisted by force of the springs on the contact fingers causes the armature to fall away from the magnet and so to

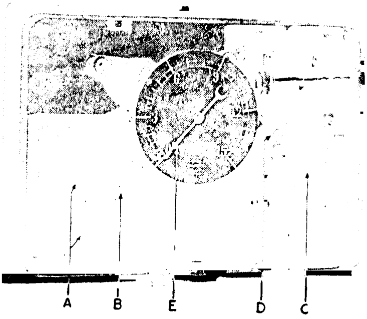


FIG. 469

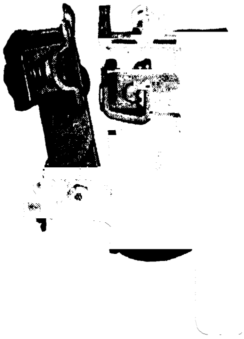


FIG. 470

carry the contact points or fingers from their contacts. Hence it is important when making an installation to see to it that this action actually occurs. The contact points of the smaller switches are small, and, in order to give long-wearing life, they are usually made of silver. For the larger switches the contact and contact fingers are ordinarily made of hard-drawn copper. The contacts for the low voltage switches are exposed, while those for the higher voltages have barriers between them, or they may be equipped with "arc chutes" which more or less cover the contacts and contact fingers. Any arc that may be formed is thus confined to its own space and tends to be quenched, thus preventing it from escaping to another contact and doing damage. Also some of the large switches are fitted with blow-out coils, which are small coils of a few turns of heavy copper wire located near the place where an arc is formed when the switch is opened. Current passing through the coil sets up lines of force that tend very quickly to blow out the arc.

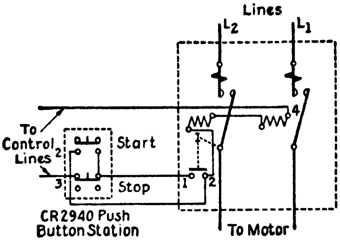


FIG. 471

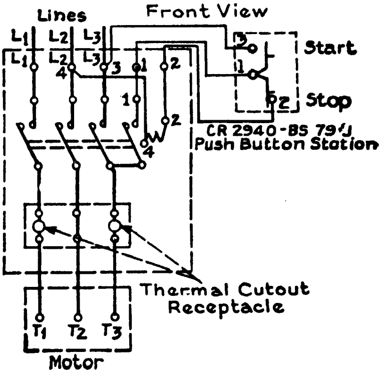

Lines
Front View
L1
L2
L3
L1
L2
L3
4
3
1
2
1
2
4
Start
Stop
3
1
2
CR 2940-BS 79'J Push Button Station
Thermal Cutout Receptacle
T1
T2
T3
Motor

FIG. 472

The connections for the magnetic switch, push button station, and single-phase motor are shown in Fig. 471. In tracing through the connections, the student should consider the push button station, shown here, to be of the momentary contact type. That is, the button (either "start" or "stop") remains depressed only so long as the operator presses down on it, otherwise it comes back to the original position. The connections in the case of a three-phase motor are shown in Fig. 472, and for several push button stations, located at different places, the connections are shown in Fig. 473. The numbers 1, 2, 3, mark the terminals of the push button station, and these terminals are connected to terminals similarly

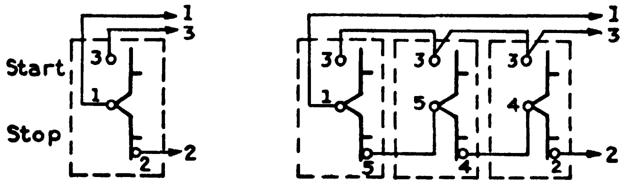


FIG. 473

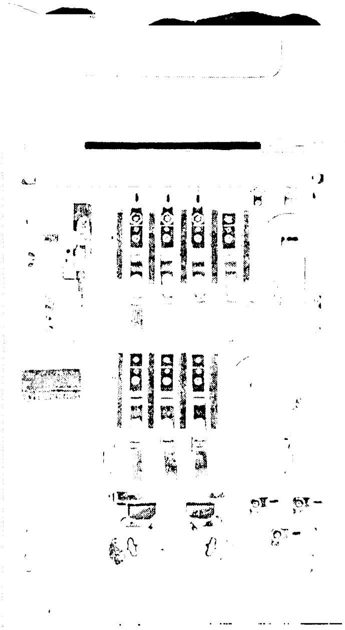
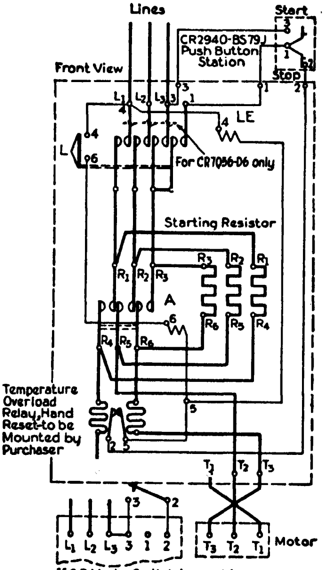


FIG. 474



If S.P Master Switch is used in place of Push Button Station connect as shown.

FIG. 474A

marked on the magnetic switch. This makes the electrician's job somewhat simpler.

Automatic starters are also available in types similar to the manually operated types discussed previously. Thus, Figs. 474 and 474A show an automatic resistor type of starter, equipped with a time-limiting device, which allows the motor to attain full speed before the resistance elements are "shorted" out of the circuit and the motor is thrown across the line. The current passing through the line contactor magnet energizes the magnet, causing it to close the line circuit through the resistors to the motor. The time-limiting device controls the operation of a second magnet which "shorts" out the resistors.

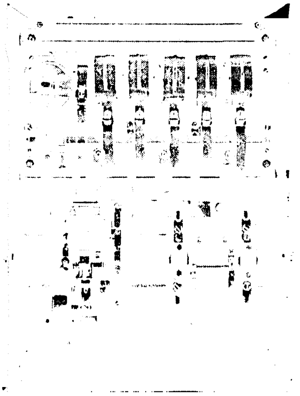


FIG. 475

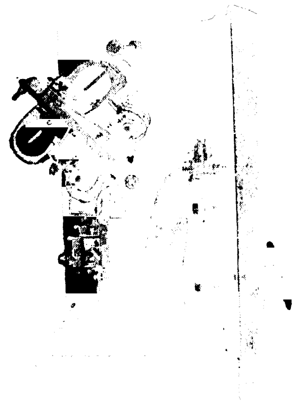


FIG. 476

The auto-transformer type of compensator is also available as an automatic compensator. Figs. 475 and 476 show such a type. An electromagnet again is used to close the contacts and a time-limiting device determines the functioning of a second electromagnet which "shorts" out the auto-transformer coils.

79. PROTECTIVE DEVICES:

Both the manually operated and the automatic type of starter or compensator may be equipped with one or more protective devices. Several of these have been mentioned. Let us examine them more in detail.

Overload protection for the motor is provided either thermally or magnetically. Thus, thermal cutouts are used often with smaller motors. Such a cutout (Figs. 477, 478) consists of a porcelain body in which is mounted a heater coil, a phosphor bronze strip, and a fusible link. The thermal cutout allows a certain overload current flow for a relatively short period of time or until the excess current has developed sufficient heating effect through the heating coil to melt the fusible link. When this has happened the phosphor bronze strip springs away from the heater where it has made contact to the position *D* shown in the picture. The fusible link holds the phosphor bronze strip in the position *C* under normal conditions.

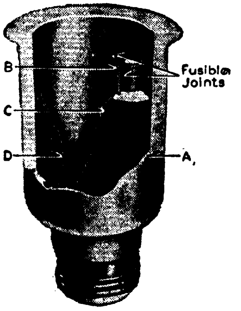


Fig. 477

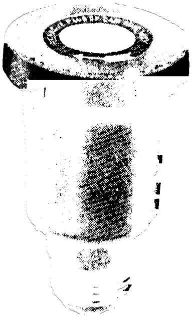


Fig. 478

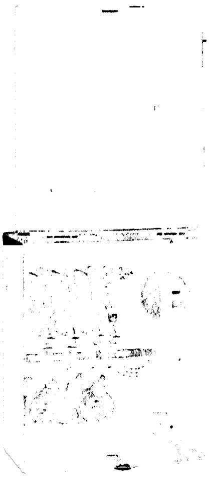


Fig. 479

Another type of thermal relay is shown in Figs. 480, 481, 482. The first shows a single element overload thermal relay, the last two, the double element type. The relay consists of a heater, a thermostatic metal strip and a set of contacts. Normally, these contacts are closed. Overload current in excess of the amount desired causes the deflection of the thermostatic strip to the point at which the contacts are per-

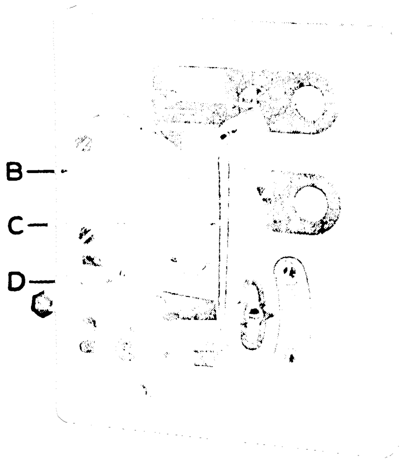


FIG. 480

mitted to spring apart, thus opening the electromagnet circuit or the holding coil circuit, and so the line wires are dis-

FIG. 481

connected. When the relay has operated to open the lines, the relay must be reset manually. Usually a push rod extend-ing to the outside of the case allows resetting to be done conveniently and quickly.

The "magnetic" overload release consists of a solenoid, a plunger, and a dash pot. See Fig. 483. A single coil will protect a two-wire line. To protect a three-phase line, two coils are necessary, one in each of two lines. The permissible current can be varied by means of an adjustable core in the solenoid. See Fig. 484. The magnet is connected in series with a line wire. When an overload current flows, the plunger is pulled up into the solenoid. In order to allow for overloads lasting for a few seconds only, the plunger has a piston attached to it which moves in a cylinder or dash pot. The piston has an opening, the size of which can be varied. The plunger moves in oil or in air, as the case may be, and it can move only as rapidly as the oil or air can pass through the hole of the plunger. As the plunger rises in the solenoid, the top of it pushes against a contact-maker, causing the circuit to be broken and stopping the flow of current to the motor. Breaking of the current also stops the flow of current through

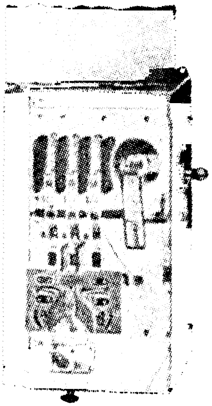


FIG. 482

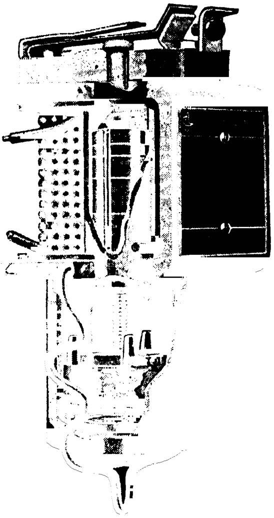


FIG. 483

the solenoid, which then loses its hold on the plunger. When the contacts are closed due to the dropping of the plunger,

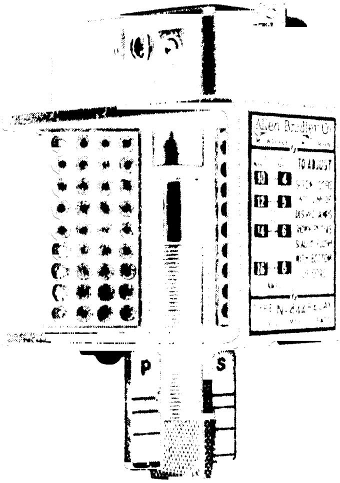


FIG. 484

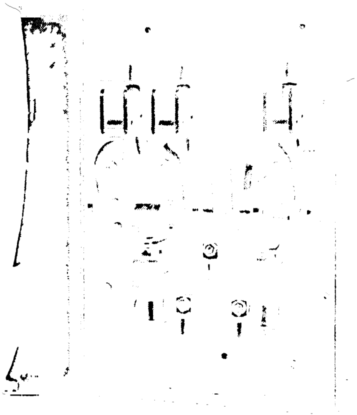


FIG. 485

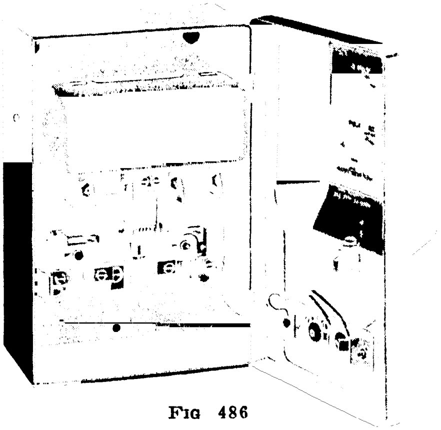


FIG 486

the overload release is again ready for operation. Fig. 485 shows a switch equipped with such an overload relay.

Still another form of overload protection is given by the Inducto-Therm relay (Fig. 486) made by the Allen-Bradley

Company. It operates on the principle of a transformer. The copper-wire winding may be considered the primary winding. Current passing through the winding causes a current to be induced in the secondary, which is made in the form of a copper tube placed inside the coil. The amount of current induced in the secondary is high and causes it to heat. Under ordinary load the heating is not sufficient to cause the circuit to be opened. When the current is increased beyond the value desired the copper tube is heated sufficiently to melt

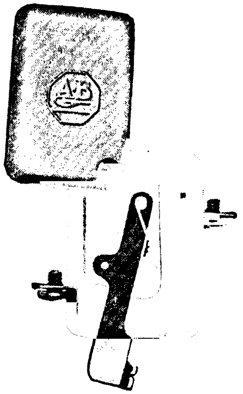


FIG. 487

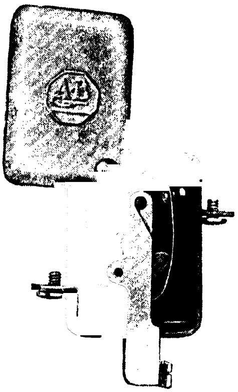


FIG. 487A

solder. The contact-making device, the reset arm, and a ratchet wheel are mounted above the coil in a little case, as shown in Figs. 487 and 487A. The ratchet wheel is not free to turn because it is soldered in place. The reset lever has a pawl attached which fits into the teeth of the ratchet wheel, thus holding the contacts "closed." When the solder melts, the ratchet wheel becomes free to turn, and so the pawl slips around with the wheel, thus opening the contacts. After a few moments the solder has hardened, once again fixing the ratchet wheel in place and permitting the reset lever to be moved to the "closed" contact position.

CHAPTER IX

ALTERNATORS

80. CENTRAL STATIONS:

The most significant feature in the development of electric power stations is the enormous increase in the power capacity of our central stations. The Pearl Street Station was installed by Thomas Edison in New York City in 1882. This station furnished direct current. The first A.C. system was installed in 1886 at Greensburg, Pennsylvania. Here transformers were first used. By 1936, the capacity of light and power systems (including private plants) had become approximately 50,000,000 Kva. About 75% of this capacity was in central stations and less than 35% of the total capacity represented water power development.

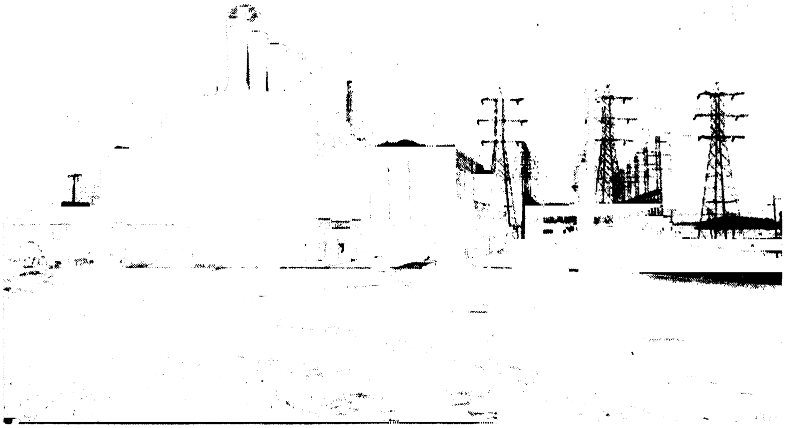


FIG. 488

The location of the central station must take into account various factors: territory to be served, accessibility of railroads or shipping for fuel delivery, character of sub-soil for foundations. Note the setting of the station in the illustration (Fig. 488). This plant has a maximum capacity of 375,000 Kva. and is part of an interconnected system of central stations which serve an area of 4,200 square miles.

Fig. 489 shows a part of the interior of a typical station.

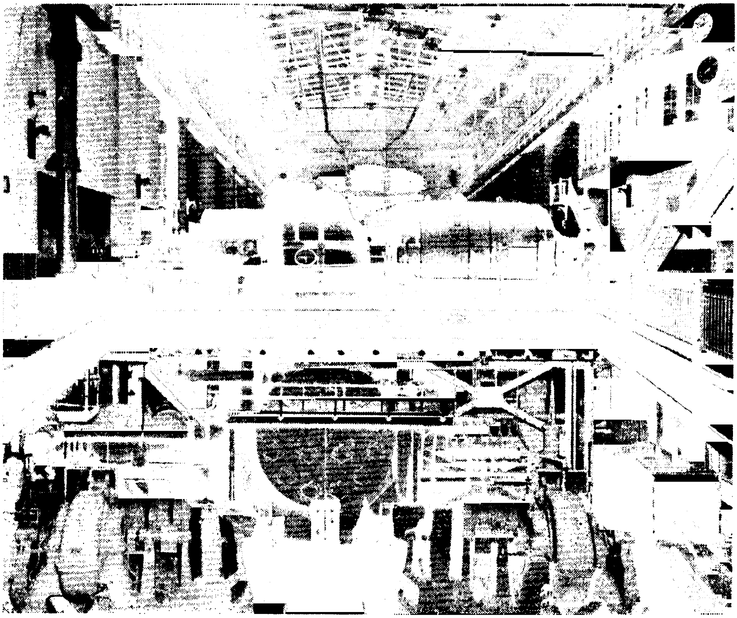


FIG. 489

In this picture are to be found most of the important units needed for the generation of electric power on a commercial basis. Observe some of these: the turbine, the generator, the steam supply pipe, the condenser, and pumps of various kinds. The boilers, the control rooms which house the various steam and electrical instruments and gauges are not shown here. A great deal of auxiliary apparatus is needed, of course, but we cannot describe all of these here.

Let us briefly consider the steps in the conversion of energy as it exists in the fuel, *coal*, over to the form of electrical energy as it is brought to the consumer by the transmission system.

Coal may be delivered either by rail or by boat, depending upon feasibility and upon freight rates. Conveyors first carry the coal (see Fig. 490), to the coal breakers which break the coal up so that the particles will pass through a ring 1¾ inches or less in diameter. Here also the coal is dried if necessary and coal dust is separated out. The broken coal is now conveyed to the coal bunkers at the top of the coal preparation house, whence it passes by gravity to the pulverizer mills. Here coal particles are ground fine as flour. The powdered coal is now conveyed to bins from which it is blown into the combustion chamber of the boiler through a special nozzle. Here the particles burn, or rather explode. About 10 pounds of air are needed to produce combustion with 1 pound of coal. The air regulation is controlled by draft fans and dampers. Observe in Figs. 490 and 491, the pulverized coal feeder pipes leading to the boiler.

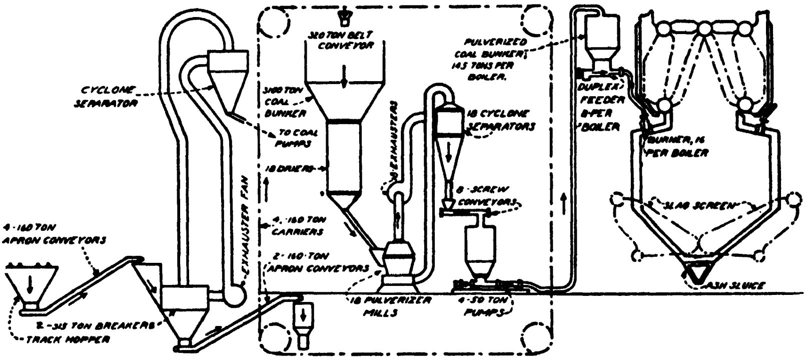


FIG. 490

The water to be evaporated into steam is called "boiler feed water." Since it is used over and over it must be absolutely pure. Before being fed to the boiler tubes it is heated so that it will cause no chilling effect on the boiler. The water is evaporated in the boiler tubes and the steam is stored in steel drums, under pressure. By passing the steam through additional tubes in the upper part of the boiler and as well in the rear, the steam is "superheated," that is, its temperature is again raised, possibly by as much as 100° to 200° F. Steam pressures and temperatures in general use vary. The temperature ranges up to 700° F. and at a pressure of 600 pounds per square inch, although higher temperatures and pressures have been used on small plants and probably will be introduced with the larger units in the future.

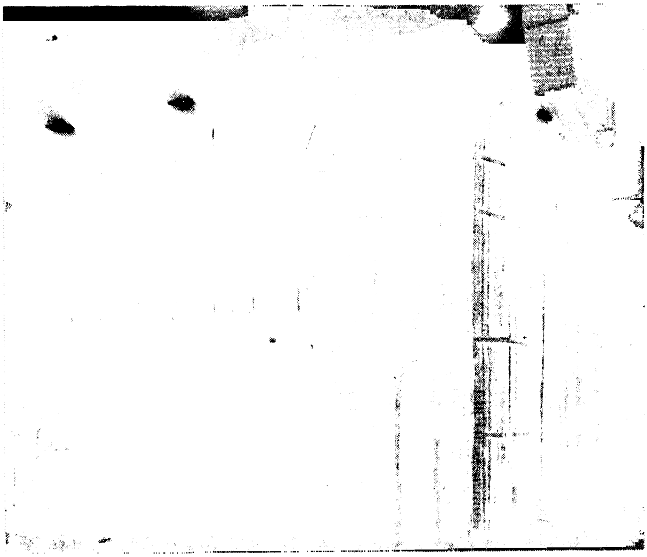


FIG. 491

The steam is now ready to be fed to the turbines. Note in Fig. 492, the turbine room, showing five units. The turbine itself is on the left of each unit, the alternator on the right. Such turbines may have a speed of 1,200 R.P.M. on units as large as 60,000 Kva. The turbine consists of alternately arranged revolving and stationary blades. The steam strikes these blades, causing rotation. Energy is taken from the steam in proportion to the temperature drop of the steam in passing through the turbine, as well as the drop in pressure. The steam exhausts through pipes which pass through the condenser, where the cooling water condenses the steam to water, thus producing a vacuum, and utilizing a maximum of the steam energy for the driving of the turbines. In a large central station, the cooling water is drawn from a nearby stream, by pumps, in quantities approximating 100,000 gallons per minute. This cooling water is returned to the river after passing through the condenser.

The steam turbine is direct-connected to the alternator and the rotation of the latter generates alternating voltage, usually as high as 13,200 volts, although some units develop voltages of 18,000 volts. From the alternator, current is fed at this voltage to transformers which raise the voltage to 24,000, 50,000, or over 120,000, as may be required for distribution to the sub-stations which redistribute the power locally. Single-phase, three-phase, and auto-transformers all are used in this plan of distribution.

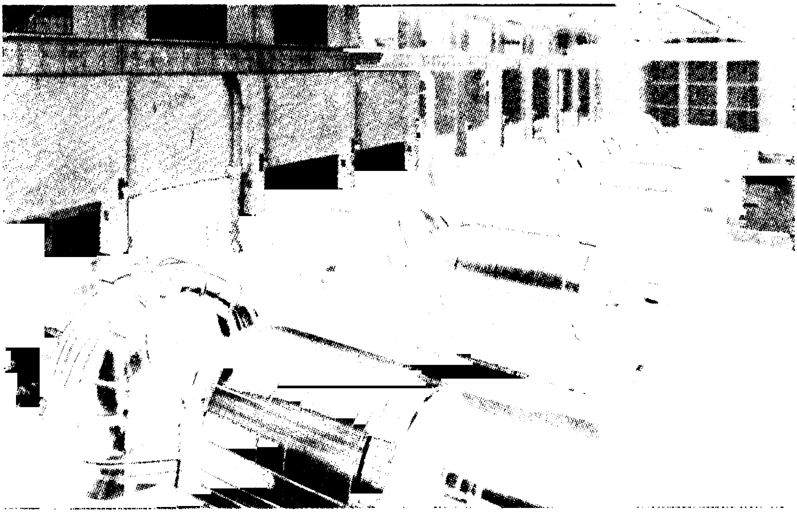


FIG. 492

81. STATION EFFICIENCY, POWER FACTOR, KILOWATT-HOUR COST:

In general, steam plant efficiencies are relatively low, but in central stations the efficiency is usually higher than elsewhere. The over all thermal efficiency of steam-electric plants ranges between 10% and 25%. The more modern plants are nearer the latter figure. This improvement in efficiency comes from the use of improved equipment, and it explains why the cost of the kilowatt-hour of electrical energy has decreased rather than increased during the last twenty-five years. A thermal efficiency of 25% seems extremely low, but compared to the efficiency of a locomotive (often no more than 8%) it is in reality exceptionally good.

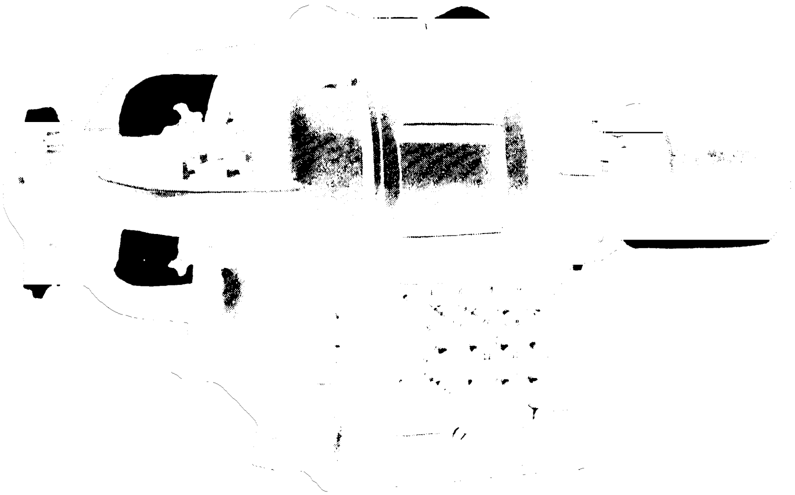


FIG. 493

Obviously the ideal power factor for a station is 100%. In practice, the plant power factor for a station is never 100%. It ranges between 70% and 95%, depending upon such factors as nature of consumer's load, hour of day, etc.

One pound of coal and approximately 10 pounds of water are at present, minimum quantities needed to produce one kilowatt-hour of energy at the alternator terminals. Relatively larger quantities of coal and water are needed for plants not so modern. The cost of producing one kilowatt-hour at the alternator ranges accordingly between one and two cents. At present (1936) unofficial figures from one municipally owned central station shows a cost of only ¾ cent per kilowatt-hour at the alternator.

82. ALTERNATOR CONSTRUCTION:

In order to study the construction of an alternator, it is convenient to consider briefly a laboratory type of A.C. generator built especially for school purposes. Fig. 493 shows such a machine built by the General Electric Company. While these alternators are small, 10 Kva. or more, they embody most of the desirable features of a larger machine and in addition are extremely flexible in that they lend themselves to a variety of uses.

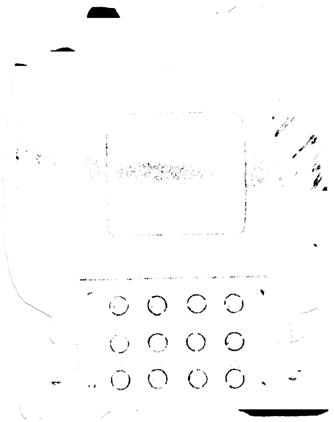


FIG. 494

The frame of such an alternator (Fig. 494) consists of steel laminations assembled between forged steel end bells, and riveted together. The bearings are bracket type, and lubrication is afforded by means of an oil ring. In large units lubrication is accomplished under pressure and the lubricating oil is passed through a purifier and a cooler before being fed to the bearing surfaces.

Note that the armature is stationary and that the field is revolving. Alternators are with few exceptions of the revolving field type. The armature conductors are placed in slots punched into the steel core of the frame. In large units, provision must be made to ventilate the machine. Ducts, punched into the individual laminations of the iron core, allow for the passage of air for cooling.

The winding placed in the slots may be "open" or "closed." A D.C. winding is always closed, that is, it enters back upon itself at the place of beginning, so as to make a continuous circuit through the entire set of coils. A three-phase delta winding is also an example of a closed winding. On the other hand a three-phase Y represents an open winding.

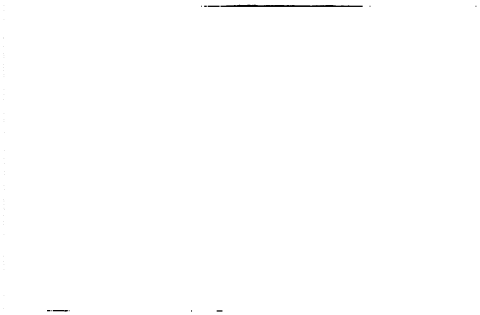


FIG. 495

The revolving field is the common "salient" pole type of construction. The field poles are dovetailed into a spider. The core is laminated steel. The shape of the pole face and the air gap have considerable influence on the shape of the voltage wave.

Large units generate 13,000 or more volts. This high voltage is possible through the use of many coils in series as well by use of strong magnetic fields. It is desirable, of course, that the wave shape approximate closely the sine wave. Such a close approximation is shown in Fig. 495, which is the voltage wave shape for the laboratory type alternator previously mentioned. Each individual coil generates its own voltage values and so has its own little voltage wave,

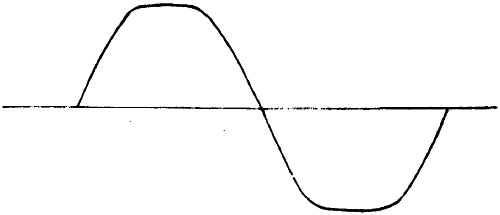


FIG. 496

but it usually is flat-topped rather than sine wave in shape. See **Fig. 496.** Several such coils joined in series not only add their voltages together, but also assist in modifying the resulting wave shape to make it sine wave in appearance. This

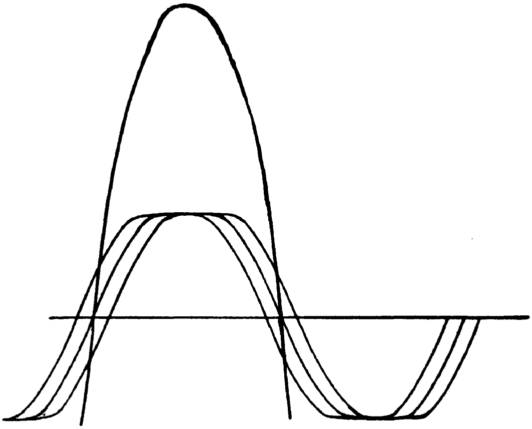


FIG. 497

is because the different coils are placed in neighboring slots, and hence do not reach the maximum simultaneously, but at intervals, depending upon the number of electrical degrees distance from slot to slot. Thus in **Fig. 497,** several voltage waves are shown, all of the same shape, but out of step by 15°. If we add these together to get the total wave, observe that not only the voltage increases, but also the shape of the wave becomes more nearly that of a sine wave.

83. THE LABORATORY ALTERNATOR:

Reference has already been made to this special type of A.C. generator built for school purposes. Note that the general construction is as already outlined above, but that in particular, the coil leads are brought outside the frame of the machine. Usually the coils on the stationary armature are arranged in six balanced groups. For convenience let us name these groups, 1-7, 2-8, 3-9, 4-10, 5-11, 6-12. The first-mentioned number in each case designates the starting-end of the coil group, the last-mentioned number in each case designates the finish end of the coil group. Thus coil group 1-7 is represented as in Fig. 498, 1 being the start, 7 being the finishing-end of the coil group.

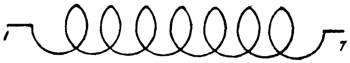


FIG. 498

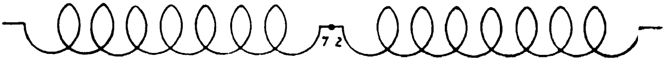


FIG. 499

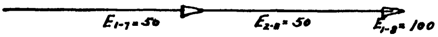


FIG. 500

In one type of laboratory alternator, coil groups 1-7 and 2-8 are in phase, and hence develop voltages in phase with each other. Therefore if coils 1-7 and 2-8 are connected in series additively, as in Fig. 499, the total voltage for the two in series or across 1-8 is 100 volts. See Fig. 500. Similarly, coil groups 3-9, 4-10 are in-phase, and so also are coil groups 5-11 and 6-12. But, coil groups 1-7 and 2-8 are both 60° E. out-of-phase with groups 3-9 and 4-10, and the latter

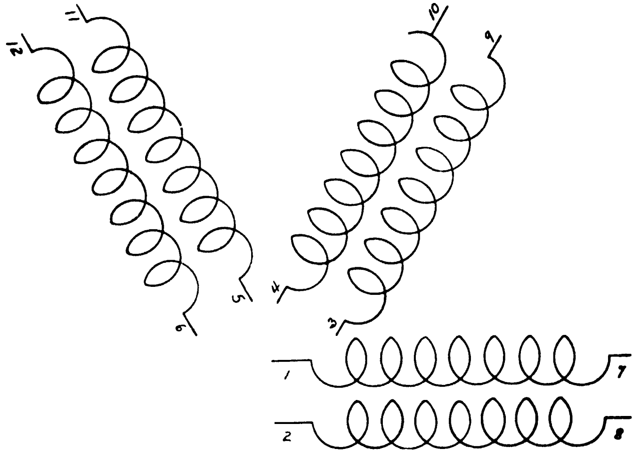


FIG. 501

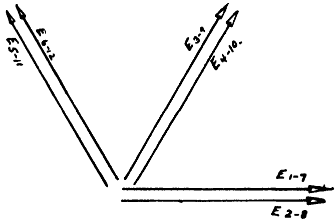


FIG. 502

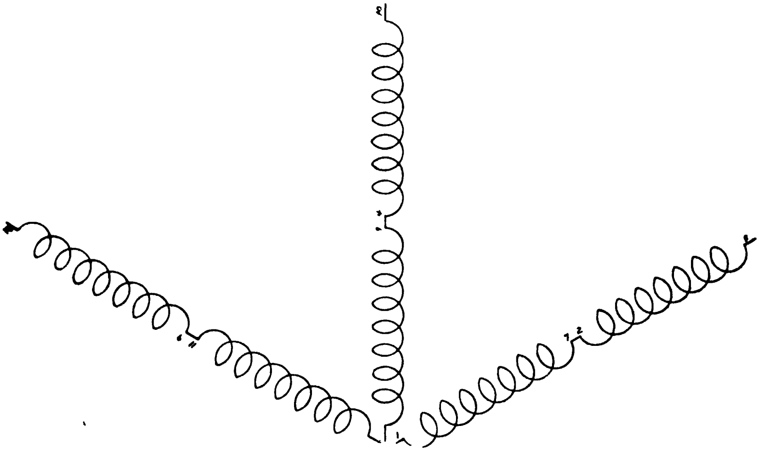


FIG. 503

in turn are 60° E. out-of-phase with groups 5-11 and 6-12. These relations are pictured in Figs. 501, 502. If now we connect each pair in additive series as in Fig. 503, we get three voltages as shown in Fig. 504, assuming that each individual coil group such as 1-7 generates 100 volts. And if we join the six coil groups in additive series we get one

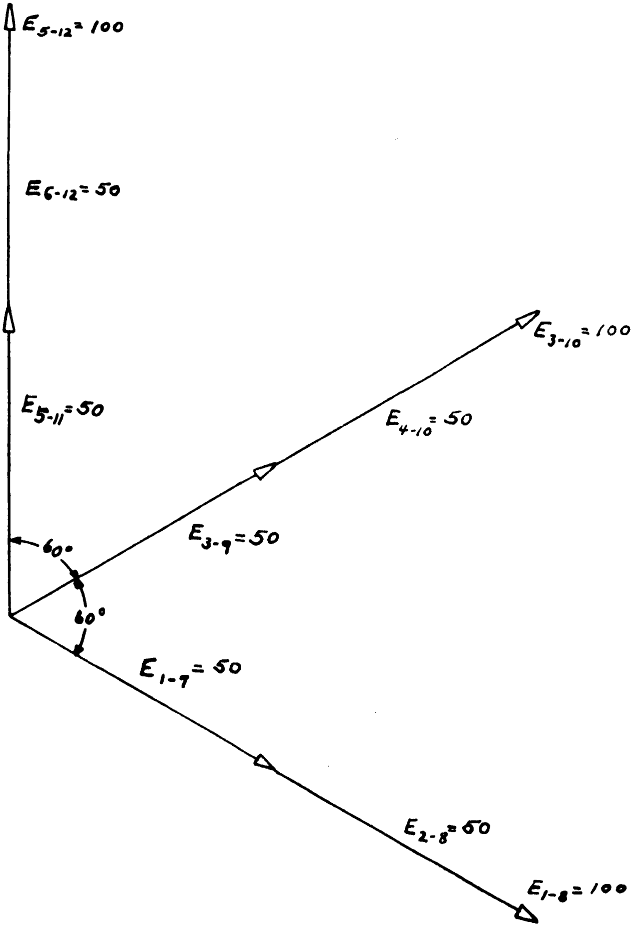


FIG. 504

resultant voltage equal to 200 volts. See vector diagram Fig. 505. This is the arrangement of the coils if the machine

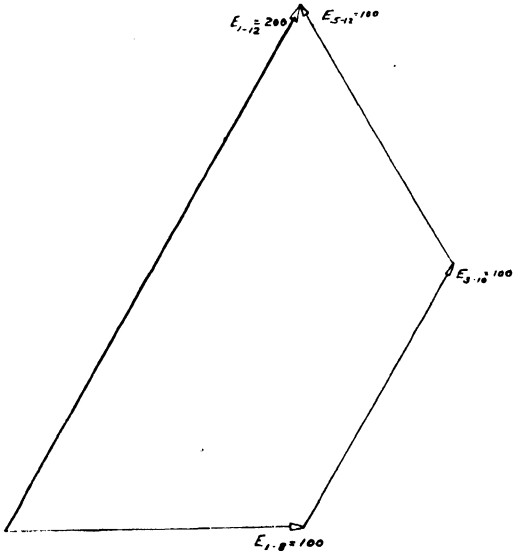


FIG. 505

is to be used as a single-phase alternator with all coils in actual use.

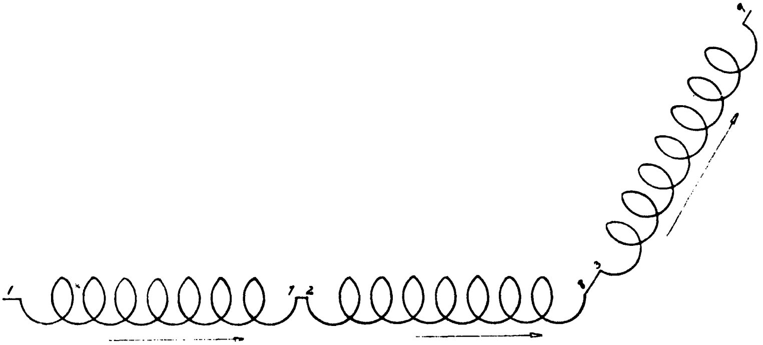


FIG. 506

Suppose, however, that the machine is to be used as a two-phase generator. The connections must now be such that the six coil groups be arranged in two divisions, each of which comprises three of the coil groups. To be a two-phase volt-

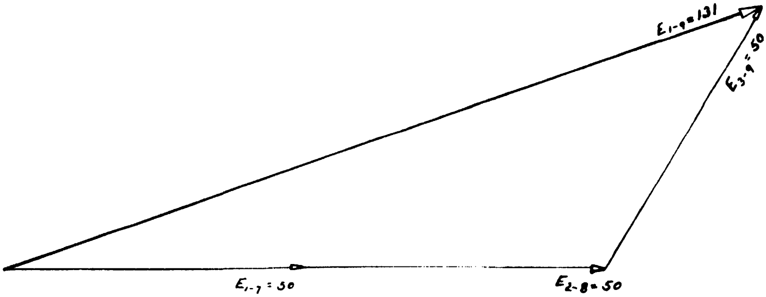


FIG. 507

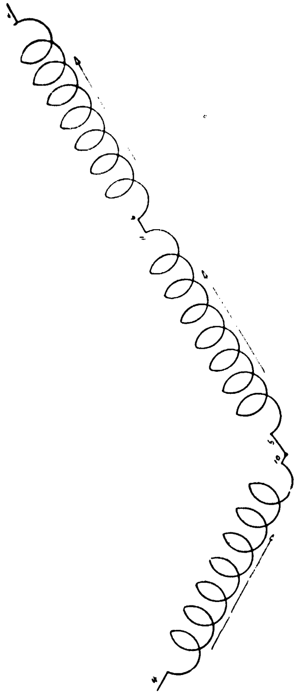


FIG. 508

age the resultant voltages of the two divisions must of course be equal and must have a phase difference of 90° E. If we join the first three coil groups in additive series as in Figs. 506, 507, the resultant voltage $E_{1\text{-}9}$ is 131 volts. Similarly, joining 4-10, 5-11, and 6-12 results in 131 volts, but at 90° E. to the voltage of the first group. See Figs. 508, 509. Hence, the two divisions containing three coil groups each now constitute a two-phase voltage source which can be used either as a three-wire or a four-wire circuit.

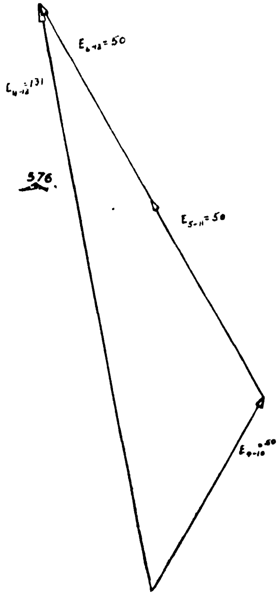


FIG. 509

Or again, if it is desired to use the laboratory alternator as a three-phase voltage source, we must obviously arrange the six coil groups in three divisions of two coil groups each; thus 1-7 joined with 2-8, 3-9 joined with 4-10, and 5-11 joined with 6-12. The results are shown in Figs. 510, 511, 512. But note that if we take the three groups *in the order above* we get three voltages of 100 volts each, but not making 120° E. with one another. See Fig. 513. But if we reverse the voltage $E_{3\text{-}10}$, as is done in Fig. 514, we have the correct

120° E. relationship required by a three-phase voltage source. Hence the start of this reversed coil must now be considered as 10 instead of 3, and the latter must be considered as the finishing-end of this phase if we wish to use the alternator as a three-phase machine.

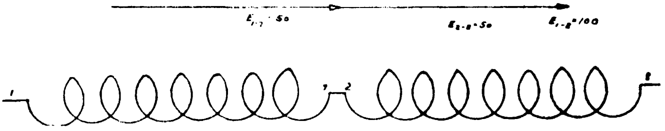


FIG. 510

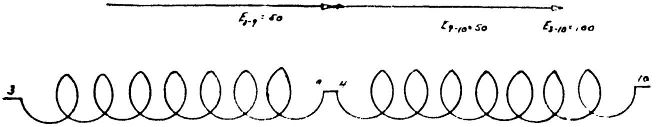


FIG. 511

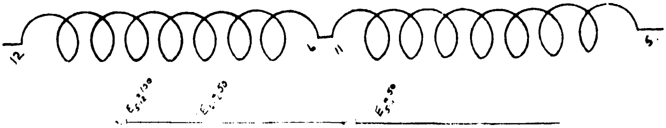


FIG. 512

To connect these phases in delta is now an easy matter.

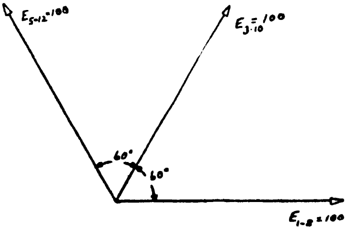


FIG. 513

The finishing-end of one phase is joined to the start of the next in closed-series fashion as shown in Fig. 515. And for the star connection, the starting- or the finishing-ends are joined in a common neutral as shown (Fig. 516).

In another laboratory type of alternator the six coils are arranged at 30° E. intervals, that is, coil group 1-7 is

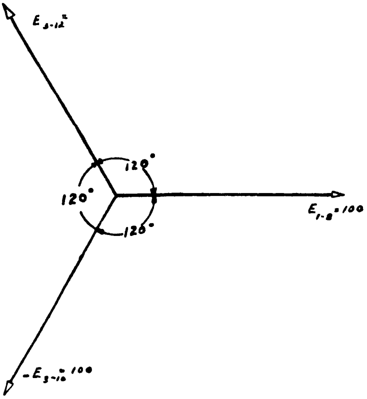


FIG. 514

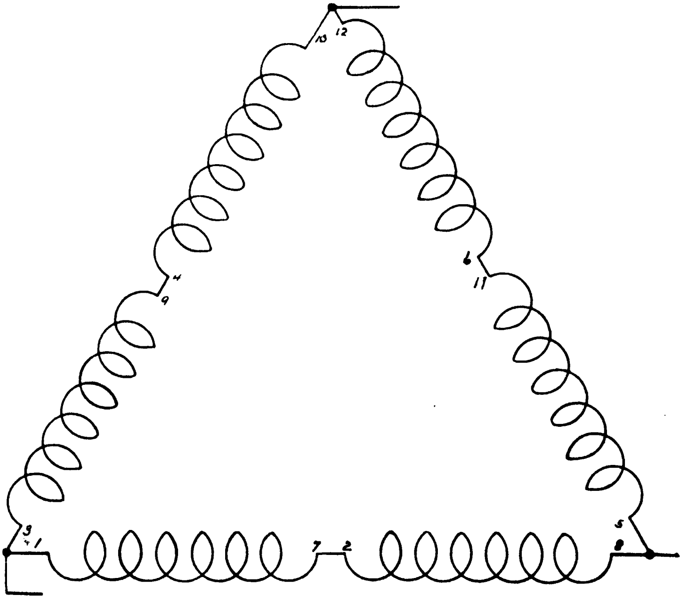


FIG. 515

30° E. displaced in slots from coil 2-8; 2-8 is 30° E. displaced from 3-9; and similarly for 3-9 and 4-10, 4-10 and 5-11, 5-11 and 6-12. For delta or star three-phase connection the plan is similar to the connections outlined above. Fig. 517 shows a symbolic arrangement of the six coil groups connected for three-phase star.

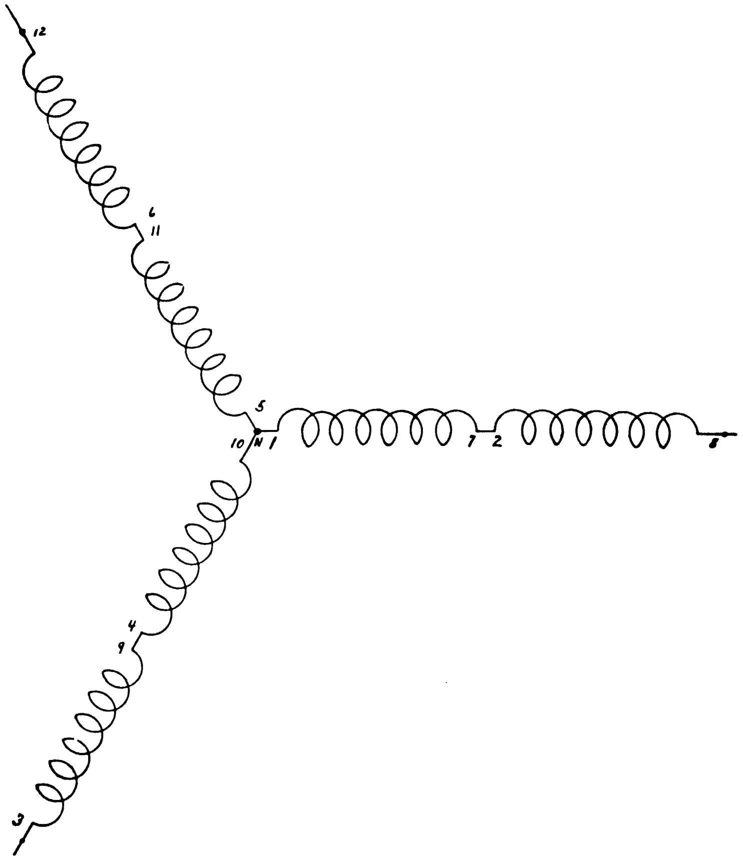


FIG. 516

84. ALTERNATOR FIELD EXCITATION:

The field current supplied to an alternator is D.C. This current is supplied by D.C. generating units at 125 or 250 volts. The field currents are therefore relatively large. Some central stations use a separate exciter for each generating unit. These are sometimes mounted on the extended shaft of the

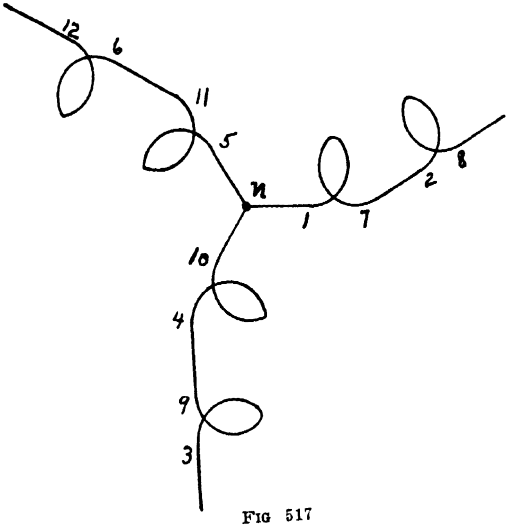


Fig 517

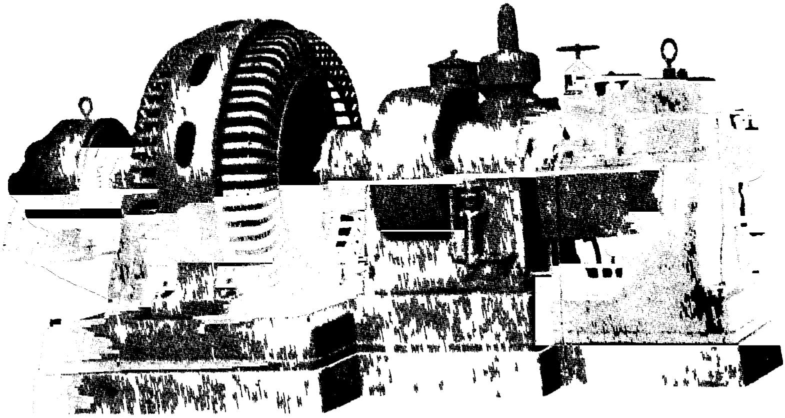


Fig 518

alternator itself. See Fig. 518. Others prefer to use two or more exciters that feed directly to exciting busses, from which current is taken by the fields of several alternators. When the exciter is not direct-connected to the alternator shaft, it is driven by an induction motor or a synchronous motor. The cost is less than driving by steam engine. A reserve field current supply may be installed also in the form of a motor-generator set, or perhaps storage batteries.

85. ALTERNATOR VOLTAGE REGULATION, ARMATURE REACTION:

It is of importance to the consumer that the voltage delivered at his service switch or transformer be fairly constant. An important hindrance to constant voltage generation is armature reaction.

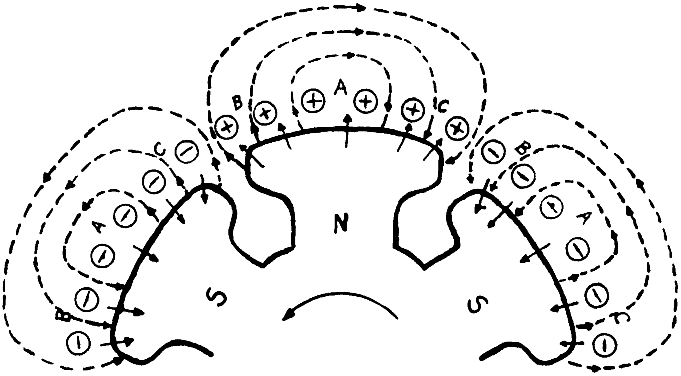


FIG. 519

Current flowing in the armature circuits exerts its own magnetizing effect on the armature core and hence influences the main field. Moreover, since an A.C. alternator armature may deliver leading, lagging, or in-phase current, the armature reaction effect on the main field varies according to the character of load as well as the size. Leading loads tend to increase voltage generated, lagging loads tend to decrease the voltage generated, while in-phase loads are neutral in this respect. This is another reason why a good power factor is desirable. Let us consider this more in detail.

Assume the load current to be in phase as in Fig. 519.

The current in phase *A* is a maximum at the instant the voltage generated by phase *A* is a maximum, or when *A* is being passed by the *N* pole middle. Current in phases *B* and *C* are shown, but they are only at half maximum value at this instant. The effect of the lines of force due to the armature current is shown to be a weakening of the trailing pole tip and a strengthening of the leading pole tip. The net weakening or strengthening effect is approximately zero, but the main field is distorted, which will affect somewhat the wave shape, but not the size of the generated voltage. As phase *A* passes from the position of maximum current and voltage,

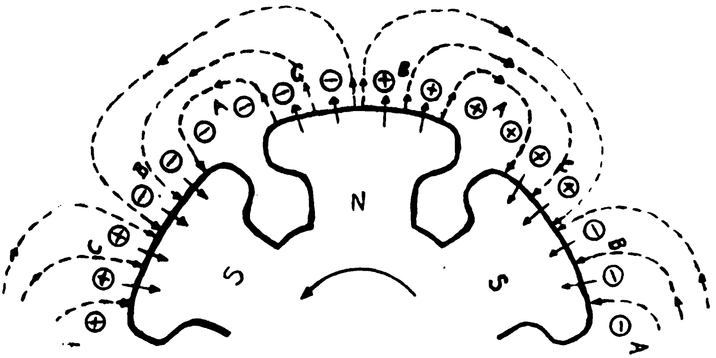


FIG. 520

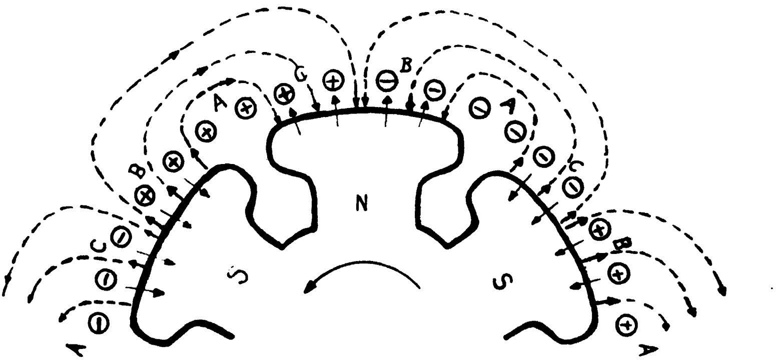


FIG. 521

phases *B* and *C* increase and decrease respectively in current value. The net effect is a constant distortion but no weakening or strengthening.

In Fig. 520, we assume a 90° leading current. Here the *N* pole middle has not yet reached phase *A*, lacking 90° E., at the moment current in *A* is maximum, since the current leads the generated voltage by 90°. Examining the lines of force, we find now that the armature lines of force coincide in direction and sense with the main field lines, and hence there is a strengthening effect, but there is no distortion. The net effect

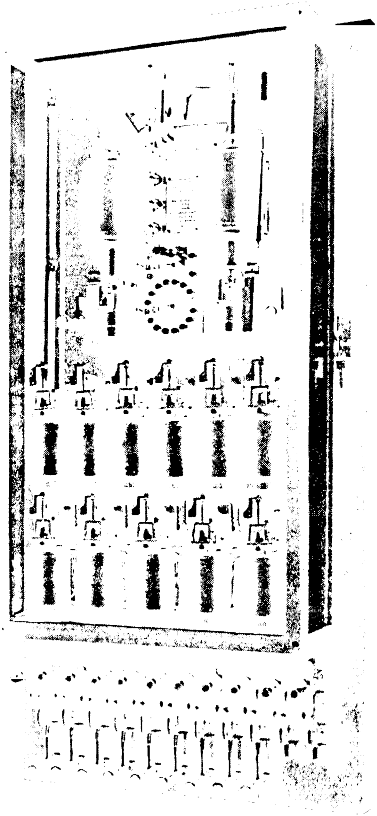


FIG. 522

throughout the cycle is therefore to increase the field strength, hence to increase the voltage generated.

Finally assume a 90° lagging current as in Fig. 521. Here the current in *A* is a maximum 90° after the voltage, or 90° after the *N* pole middle has passed *A*. The lines of force due to the armature current are now in opposition to the field pole lines. Hence the lagging current tends to decrease the field pole strength and thus causes a decrease in generated voltage.

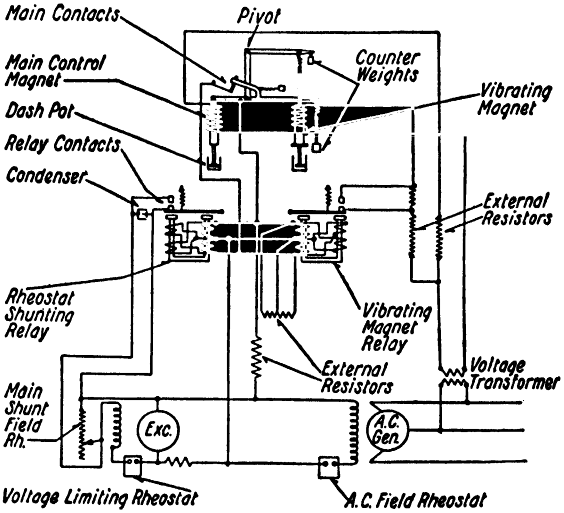


FIG. 523

It is obvious that if load changes affect the generated voltage, constant voltage can be maintained only by some form of outside control such as by field rheostat. But control by field rheostat is not sufficient to accommodate the rapid fluctuations of voltage that occur in a large system, and which though not necessarily large must be ironed out to give a constant voltage.

This is accomplished in addition to rheostat control by an operator, by the use of an automatic voltage regulator. Such a regulator is shown in Fig. 522. The connections of a regulator are rather complex. A simplified diagram appears in Fig. 523. It shows a regulator to consist of electromagnets, levers, and contacts whose ultimate purpose is to "cut out" or "cut in" the exciter field rheostat, so as to permit a larger or a smaller field current to flow to the alternator field coils, thus increasing or decreasing the generated voltage in accordance with the opposite action caused by the load current. The regulator acts very rapidly. In fact its contacts are opening and closing in rapid succession continuously.

The voltage regulation of an alternator should of course be close. That is, the voltage should not vary much between zero and full loads. Voltage regulation is usually expressed

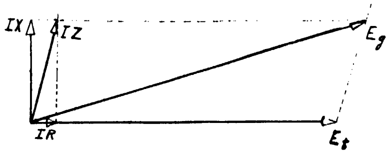


Fig. 524

as a percentage of the full load terminal voltage of the alternator. Thus,

$$\text{Voltage regulation} = \frac{E_{\text{zero load}} - E_{\text{full load}}}{E_{\text{full load}}}.$$

The voltage regulation may have a negative value, which would occur when the alternator furnishes leading current. The zero load voltage is lower in this case than the voltage with load, since leading current results in armature reaction tending to make the generated voltage rise. This condition is not met with in practice since station loads are usually lagging.

Armature reaction is not alone responsible for a variation of the terminal voltage of the alternator. Since the alternator armature coils have both resistance and reactance a portion of the generated voltage is used to push current through the winding (against resistance and reactance hindrance) to the outside lines. Hence this portion is not available at the terminals. Fig. 524 illustrates this. The vector E_g represents the total voltage generated by the armature. Assuming a load current in phase with the terminal voltage E_t, IR represents the voltage required to push I amperes through a coil resistance equal to R ohms. This IR vector lies on the E_t vector since we have assumed $\cos \Phi = 1.00$. Similarly IX represents the voltage required to offset the reactance of the armature coils. This vector is, as usual, at 90° to IR. The two together give IZ, the impedance drop over the armature coils. Now the alternator must generate the IZ volts needed by the armature itself and the E_t volts, the terminal voltage supplied to the line. Hence the total voltage generated by the alternator is the vector sum of these two as shown. Another way of stating this is that from E_g the total generated voltage must be deducted the IZ volts needed to push current through the armature impedance, leaving E_t terminal volts for the line. Hence, even though the alternator is operating at unity power factor, its voltage regulation is not zero, since the terminal volts at zero load are equal to E_g volts, and as the load increases IZ increases and E_t therefore decreases.

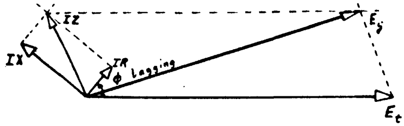


FIG. 525

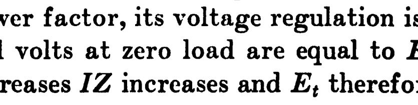


FIG. 526

For lagging current loads, the condition is shown in Fig. 525, and for a leading load, as in Fig. 526.

The graphs in Fig. 527 show not only the voltage load characteristic of an alternator under conditions of varying load, but, in addition, they show that this characteristic varies as the power factor varies.

86. PARALLEL OPERATION OF ALTERNATORS:

Central stations commonly install several turbo-alternator units to attain the total plant power output. These units are operated in parallel. Let us determine what conditions are essential for doing this safely, and also how these conditions are attained. For our purpose we shall discuss the single-phase alternator, keeping in mind that all that follows applies equally well to each phase of the three-phase machine. Let us assume two alternators connected in parallel as in Fig. 528. Examine this illustration carefully. Note that

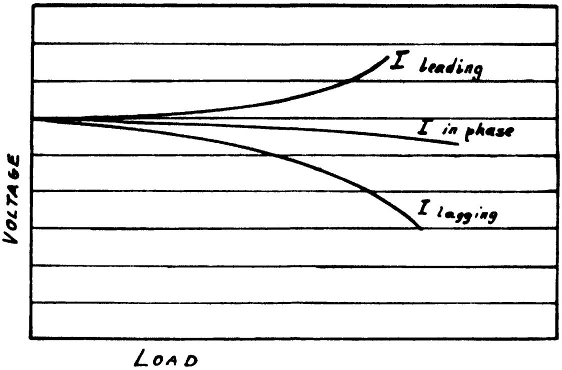


FIG. 527

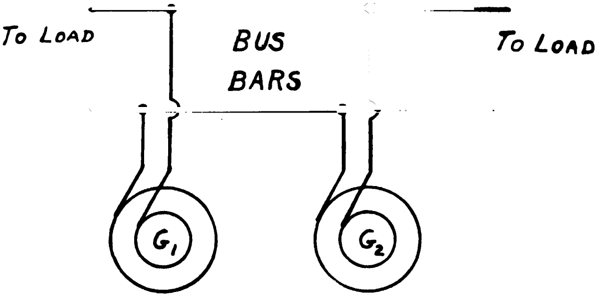


FIG. 528

through the bus bars, the armatures of the two generators form a complete electrical circuit. This is again shown in Fig. 529. Both machines must produce positive polarity on the one bus bar, and negative on the other, at the same instant. Assuming the positive direction at any given instant as shown in Fig. 530, observe that within the local circuit between the two machines there is opposition, that is, the two voltages generated oppose each other, which is as it should be since otherwise a large current would flow in the local circuit. Also since the voltages are alternating it is essential that both machines generate voltage at the same frequency. The two machines must moreover be in step. Both might generate 60-cycle voltages, but might be out of step by half a cycle which would be the case if they were connected to the bus bars with the wrong polarity.

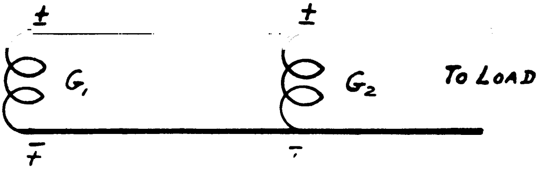


FIG. 529

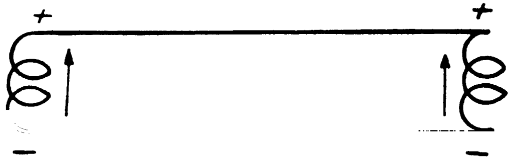


FIG. 530

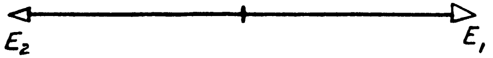


FIG. 531

Now assume that both machines are generating the same frequency and the same voltage, and that they both put the same polarity on the bus bars, then we can picture this condition by vectors as in Fig. 531. Here E_1 and E_2 are equal and opposite for the local circuit and so neutralize each other during all instants of the voltage cycle. Hence no current flows between the two armatures.

Now suppose that E_2 is larger than E_1, though the frequency is exactly the same. Then (Fig. 532) there is a net voltage between the two armatures which will cause current flow against the opposition of the impedance of the two armatures. This current I_s lags somewhat less than 90° behind the voltage E_R, since the armature coils have a relatively large reactance compared to their resistance. I_s is a current circulating between the two armatures, serving merely to heat these armatures without contributing to the power output. The current I_s is called "synchronizing current." Its action is such as to try to equalize the voltages E_1 and E_2 across the bus bars. I_s is large because the armature impedances are limited. Hence it exerts considerable influence on armature reaction in each machine. Note that I_s referred to alternator No. 2 lags behind E_2 and referred to alternator No. 1 it leads E_1. Hence armature reaction due to I_s in No. 1 will tend to increase E_1, whereas in No. 2, E_2 will tend to be decreased. Thus E_1 and E_2 tend to be equalized due to the action of I_s and this is, of course, a very beneficial effect of

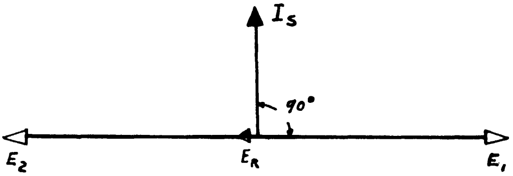


FIG. 532

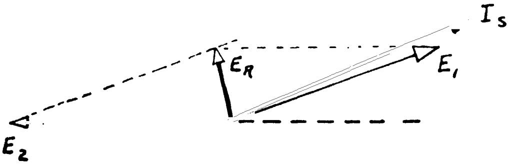


FIG. 533

the synchronizing current. Nevertheless, ideal conditions demand that E_1 and E_2 be equal so as to reduce I_s to zero.

E_1 and E_2 could be equal but not exactly opposite in sense, and then again synchronizing current will flow. Thus in Fig. 533, E_1 and E_2 are equal, but E_1 has advanced with respect to E_2 by about 20°. Note that again there is a resultant voltage E_R between the two armatures and a synchronizing current I_s. The latter is again about 90° behind E_R. But now I_s is almost in phase with E_1. In Fig. 532, alternator No. 2 is pumping the current I_s through alternator No. 1. The latter is therefore really operating as a motor (synchronous), while No. 2 shows generator action. The power it delivers to No. 1, by means of the synchronizing current causes No. 1 to speed up or move faster. Hence E_1 tends to assume some position as in Fig. 533. Here, however, I_s is nearly in step with E_1. Hence No. 1 unit now furnishes synchronizing power to No. 2, and the latter now shows motor action. These two illustrations (Figs. 532, 533) may be considered as extremes. The action of the alternators does not proceed as far as these pictures would seem to indicate. They do show, however, that voltage inequalities, or inexact frequencies, or instantaneous speed changes all cause a synchronizing current whose function is to smooth out the differences between the two machines so as to permit operation in parallel with a minimum of power loss due to heating. When the differences in frequency or voltage or the speed variations are large, the current I_s is proportionately larger and instability of the two machines results. This condition is marked by an apparent "hunting" of the machines for correct synchronous conditions at which operation together is possible, and is manifested by a peculiar throbbing hum occurring while the machines are in process of reaching a condition of equilibrium.

To make certain that conditions are proper to permit an additional alternator to be connected to the bus bars, when one or more are already in operation it must be ascertained first that the voltage of the incoming machine is the same as that of the bus bars; second, that the frequency of the incoming machine is the same as the bus-bar frequency; third, that similar leads from the alternators are joined to the bus bars; and finally that the wave shapes of the machines are alike.

The latter two conditions are of little importance to the operator, since the design of the machine takes care of the wave shape, and the correct lead connections are made at the time of installation. But it is necessary that the first two conditions be ascertained before closing the switch which

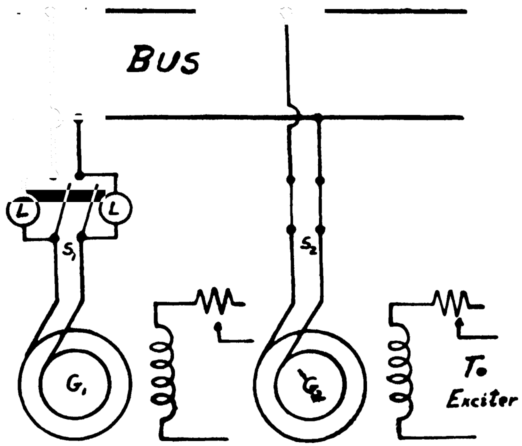


FIG. 534

throws the incoming unit onto the bus bars. The apparatus used to determine correct paralleling conditions (of synchronism) are a voltmeter and a synchroscope. The latter may be replaced by incandescent lamps. The connections are shown in Figs. 534, 535.

Unit No. 2 is carrying the station load at the present time. No. 1 is to be thrown on the bus bars to share the load with No. 2. The prime mover of No. 1 is first brought up to speed. The field rheostat R_1 is adjusted so that alternator No. 2 generates voltage equal to the bus voltage. In practice it is desirable that this incoming machine generate a slightly higher voltage than the bus bars. This makes certain that the incoming machine will not draw current from the bus bars at the moment its line switch is closed, a condition that might cause considerable trouble.

When No. 1 generates the voltage desired, we must next ascertain whether the frequency of No. 1 is the same as that on the bus bars. The synchroscope or the synchronizing lamps enable us to do this. Connected as in Figs. 534, 535, the lamps are a part of the local circuit formed by the two generator armatures. Any current flowing in this circuit must pass through the lamps. The latter have sufficient resistance to reduce this current to a safe amount. If the voltages generated are higher than 110 volts, two 110-volt lamps should be used in series in each line. For voltages above 220, it may be necessary to use transformers to bring the voltage within the range of the lamps.

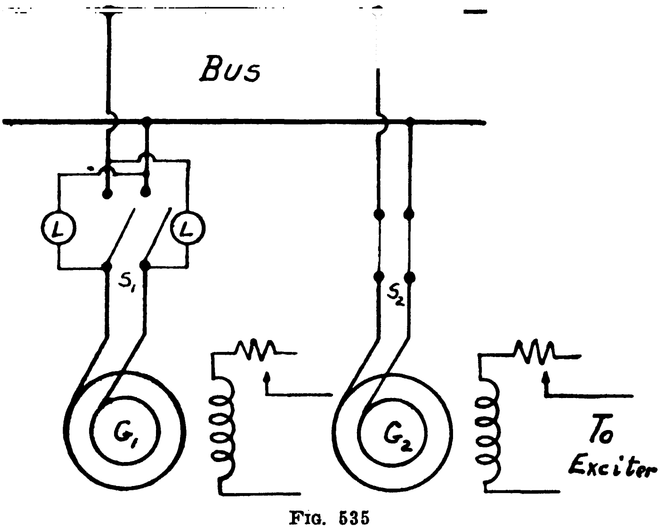


Fig. 535

Now with connections properly made, and the voltage of the incoming machine adjusted to be equal to the bus voltage, if a current flows through the lamps as indicated by the brilliancy of the light, it is not due to excessive voltage on either the bus side or the incoming machine side, since the latter voltage equals the bus voltage. Such current must then be due to a difference in generated frequency. If the lamps remain permanently bright, the frequency on the bus bars and that of the incoming alternator are far apart, which means that the No. 1 unit (incoming) is running either too slowly or too fast. Adjustment of the speed of No. 1

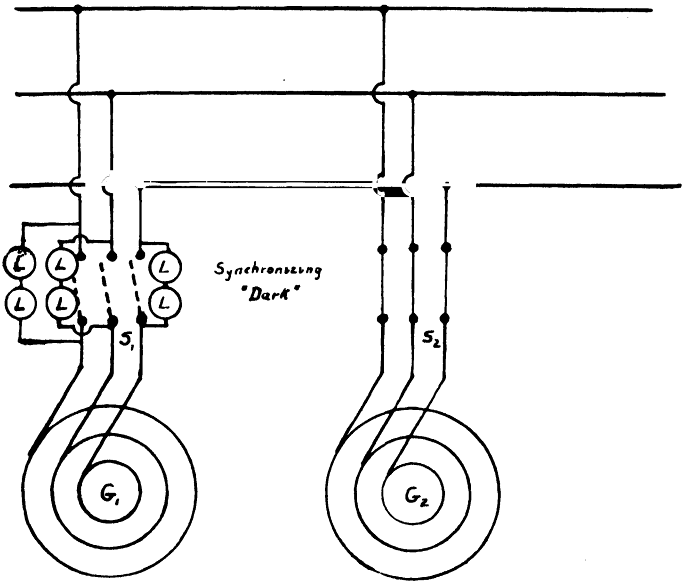


FIG. 536

soon brings about a condition of pulsating brightness in the lamps, that is, the lamps become dim, then dark, then gradually return to full brightness again. When this occurs, the frequencies of the two units are nearing equality. Continued adjustment of the No. 1 speed gradually shows up these pulsations of brightness, until the lamps remain dark for relatively long periods. When this condition is reached, the lamps indicate that no current flows in the local armature circuit, hence the two units are now in synchronism, that is, they are running in step, producing the same frequency. We are not quite ready, however, to close the switch which puts No. 1 on the bus bars. The adjustment of the speed of this unit has probably changed its generated voltage, hence we must check up on this voltage, and if necssary readjust the field current. Now the switch can be closed, if the lamps still indicate long dark periods, and this should be done as nearly as possible at the middle of the dark period.

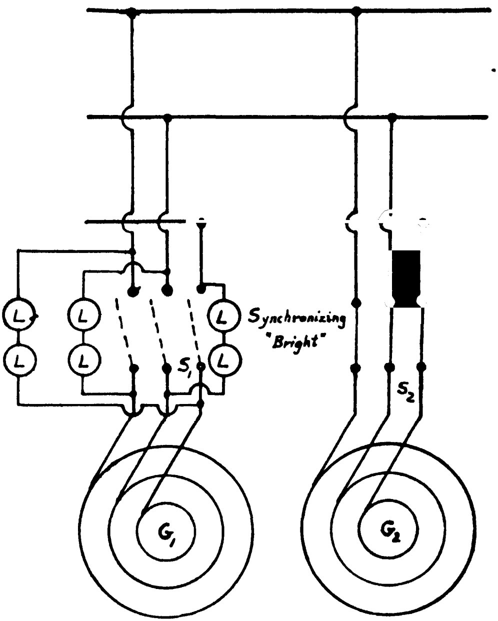


Fig. 537

When the lamps are connected as in Fig. 535, which is across the line rather than in the line, the synchronizing lamps behave just as before, but agreement of frequency is indicated by maximum brightness rather than by darkness. Hence the switch putting the incoming generator on the bus bars is closed at the middle of a bright period.

The procedure for paralleling alternators is called ***synchronizing***. For three-phase alternators the process is very much similar. There is one difference, however. Since there are three phases, it is important that the order of the phases in the two units to be paralleled be the same. The synchronizing lamps (Figs. 536, 537) indicate this correctness of phase rotation by the character of the brightness pulsations. If the lamps grow bright and dim together, phase rotation for the two units is the same. If some lamps grow bright

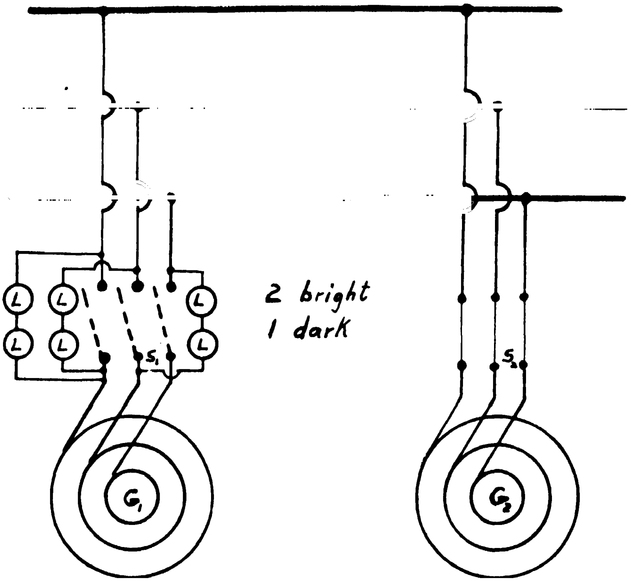


Fig. 538

as others grow dark, then the phase rotation is not the same and correction is made by simply reversing any two line wires from the incoming generator. The latter condition is not usually met with in a central station, since correct phase rotation is established at the time a unit is installed. Fig. 536 shows the connections for synchronizing by dark lamps, Fig. 537, by bright lamps. A third method, which combines the other two, is shown in Fig. 538. Here one lamp is connected for "dark" synchronizing and two lamps for "bright." This last method is preferable because by contrast of dark with bright lamps, the middle of the period is more easily determined.

87. EQUALIZATION OF LOAD:

Variation of the alternator field current by field rheostat adjustment does not bring about a shifting of load from one alternator to another. As was pointed out previously, when two alternators run in step, but generate different voltages, a synchronizing current I_s circulates between the two armatures which tends to equalize the two voltages at the bus bars by armature reaction in the two machines, but with little effect on the division of the station load between the alternators. In order to make an incoming unit take load after it has been properly put on the bus bars, it is necessary to raise the speed of its prime mover. When the unit has been properly paralleled, it merely "floats" on the bus bars in the sense that it really gives no power to the system, nor does it take power from the system. It is merely ready to give or take, depending upon what changes are made. If the speed of its prime mover be raised, more power is put into the alternator, and hence it can give out power to the system, in other words, carry some of the load. This change in speed in the alternator is momentary only. The rotor of the alternator moves faster than the other rotors for an instant, causing its voltage to step slightly ahead of the other voltages. The added load taken because of the phase relationship changes is sufficient to hold the rotor at the same speed as the other rotors but slightly advanced in phase with respect to the others.

88. THE SYNCHRONOUS CONDENSER:

When an alternator is to be withdrawn from the bus bars, its speed is first dropped to the point at which the power output of this unit, as shown by the wattmeters, is zero. The ammeter may still show some current output, but this current is reactive, since the wattmeters show zero power. The current is now reduced to zero by adjusting the field current of the alternator, after which the line switch may be opened without danger of damage to the equipment. The alternator is still turning over, however, and may be shut down by cutting off the power supply to the prime mover.

Suppose, however, that power to the prime mover is shut off before the line switch is opened. The alternator continues to run at synchronous speed, but it now takes power from the system. In other words, it is being driven as a motor and runs idly, in the sense that it has no useful power output. Moreover, by varying the field current of this alternator it can be made to take leading or lagging current from the bus bars. An alternator used in this way is called a synchronous condenser, because it has for its purpose the correction of station power factor. The field current is increased so as to make the current taken by the alternator (now running as a motor) a leading current, which corrects for the lagging currents usually demanded by industrial loads. The synchronous condenser is in reality an alternator turned about, and run as a synchronous motor, except that the synchronous motor usually is also expected to give power output by driving machinery.

PROBLEMS—CHAPTER IX

1. Draw a symbolic winding diagram for a four-pole three-phase star-connected alternator.
2. Draw a symbolic winding diagram for a six-pole three-phase delta-connected alternator.
3. At what speed must the alternators in the preceding problems be run to generate a 60-cycle voltage?
4. An alternator delivers 50,000 Kw. at 80% power factor. What is its Kva. rating?
5. What power will the alternator in problem 4 deliver when operated at 100% power factor?
6. If the alternator in problem 4 generates 13,200 volts, what is its full load current rating at 80% power factor? At unity power factor?
7. Two alternators operate in parallel. The first is rated at 50,000 Kva. (45,000 Kw. at 90% power factor) and the second at 33,333

Kva. (30,000 Kw. at 90% power factor). Both generate 13,200 volts. When the station load is 62,500 Kw. at 90% power factor what should be the fair load on each unit?

8. Suppose the station load to be the same as in problem 7, but the power factor of the second unit to be 80%. What is the fair division of load for the two units?
9. On the basis of 1 pound of coal and 10 pounds of air required to produce one kilowatt-hour at the generator terminals, how much coal and air are required to produce a mean daily load of 240,000 kilowatt-hours?
10. At one cent per kilowatt-hour at the generator compute the cost of producing the mean daily load for one year.

CHAPTER X

TRANSFORMERS

89. THE TRANSFORMER PRINCIPLE:

In the study of reactance and inductance, the student learned that the reactance of a circuit expressed in ohms is merely a convenient way of translating the opposition of back-voltage in a circuit into the same terms (ohms) in which we express resistance.

Now if the alternating current flowing through a coil and the alternating magnetic flux resulting from this current can so influence the coil as to make it induce a counter-voltage, would not a similar result be attained in a second coil when brought within the influence of the first coil? Of course, the answer is affirmative. A voltage is induced in the second coil, if the alternating flux links with the turns of the second coil. A transformer is simply an arrangement of two coils on a common steel core that applies the principle of induction just referred to. An alternating current supplied to coil *A* (Fig. 539), produces an alternating flux within the common steel core. This flux sets up in *A* the back-voltage which we have been expressing as reactance in all of our discussions. But this same alternating flux sets up in coil *B* a voltage like the back-voltage in *A*, although coils *A* and *B* have no electrical

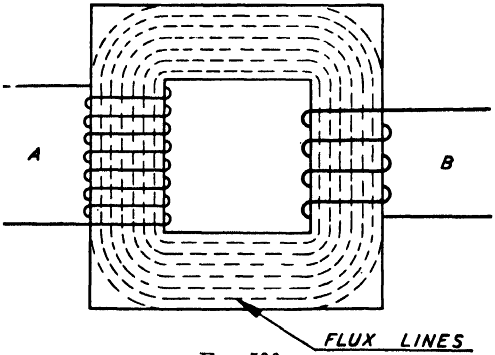


FIG. 539

connection. The size of the voltage induced by either coil depends upon the number of flux lines and also the number of turns in each coil. As shown in the illustration (Fig. 539) the number of flux lines (except for negligible leakage) that link the two coils is the same. But coil *A* has six turns, coil *B* has three turns. Hence the voltages induced by the two coils are approximately as 6 : 3 or 2 : 1, or directly in proportion to the number of turns. Moreover, the back-voltage induced by coil *A* is very nearly equal to the impressed voltage on coil *A*. Hence we make only a negligible error when we say that the voltage impressed on coil *A* has the same ratio to the induced voltage in coil *B* as the number of turns in *A* bears to the number of turns in coil *B*.

$$\frac{\text{voltage impressed on primary}}{\text{voltage induced by secondary}} = \frac{\text{turns in primary}}{\text{turns in secondary}}$$

The above is another way of stating this, except that we have given the two coils a definite name: *primary* and *secondary*. The primary coil is the coil which receives power from the source; the secondary coil is the coil which delivers power to the load. The equation,

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

is the mathematical form of the above statement.

In the illustration chosen, the primary has twice as many turns as the secondary coil. The secondary-induced voltage is therefore only half of the primary impressed voltage. A transformer used in this way is called a *step-down* transformer, since it changes the voltage from a higher to a lower value. Some transformers are built mainly for this purpose. Others are intended to raise voltages. In these the primary coil has fewer turns than the secondary. Such transformers are called *step-up* transformers.

The convenient and simple manner in which A.C. voltages are raised or dropped by transformers, and the great saving in power and line drop in transmitting power at high voltages has been an all-important factor in the widespread use of alternating rather than direct current. Large quantities of power are transmitted at high voltages and with relatively small currents with little loss by the use of transformers at both ends of the transmission line, one set as step-up, the other set as step-down transformers.

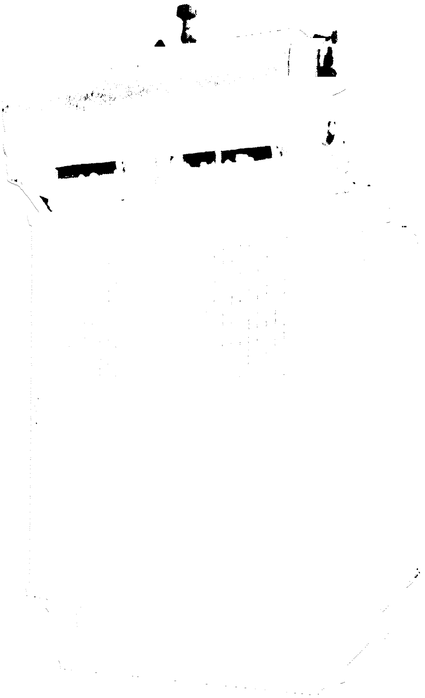


FIG. 540

90. TRANSFORMER CONSTRUCTION:

Transformers are built in a large variety of sizes and types, for many different voltages, and also as single-phase transformers and three-phase transformers. The size, type, voltage, etc., are determined by the kind of service to be rendered, as also by the peculiar design of a given manufacturer.

Single-phase transformers are preferable to three-phase, because of the marked advantage of the former over the latter in case of trouble. Moreover, three single-phase trans-

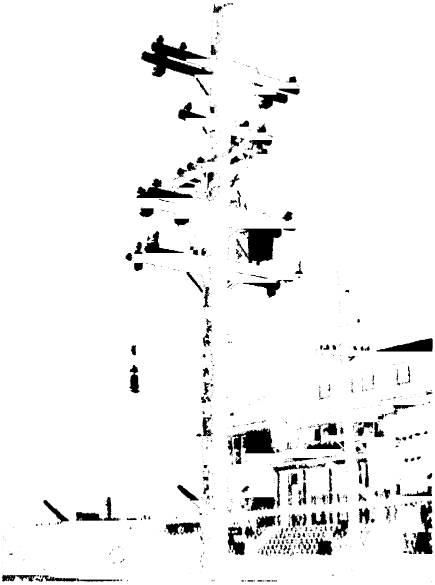
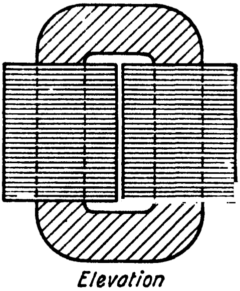


FIG. 541



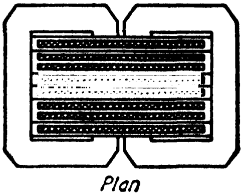


FIG. 542

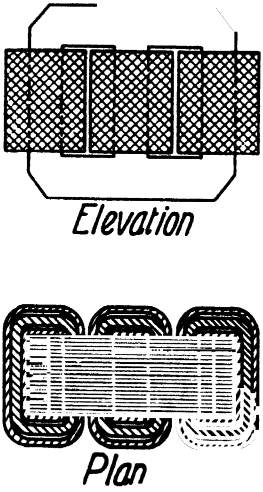


FIG. 543

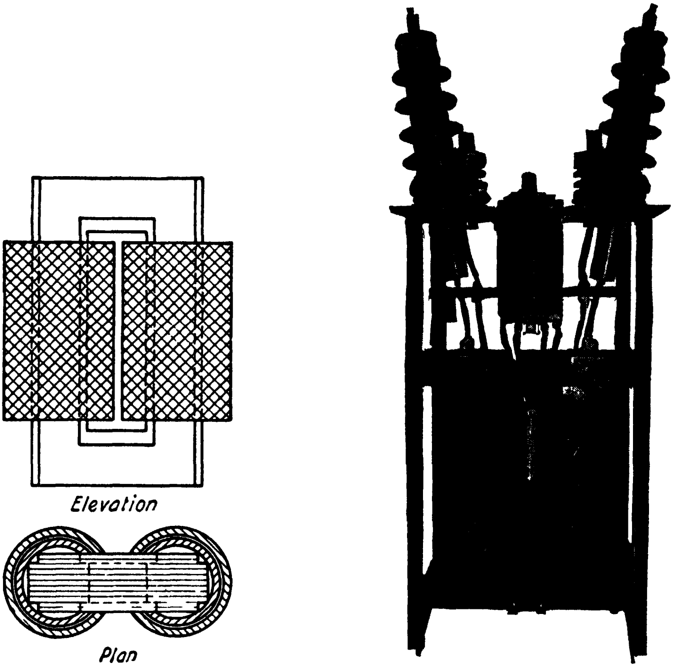


Fig 544

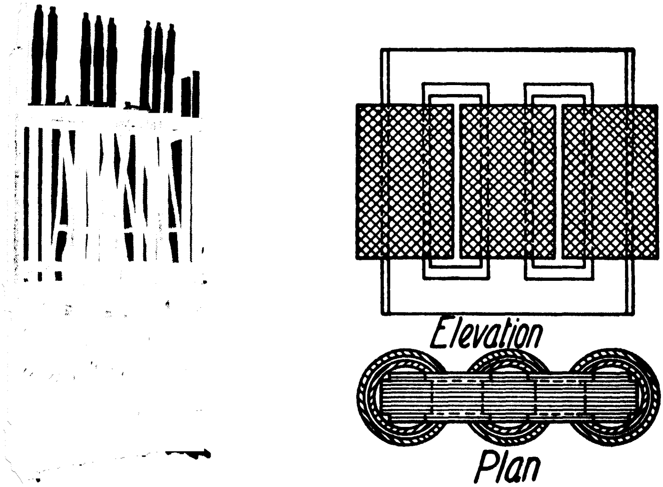


Fig. 545

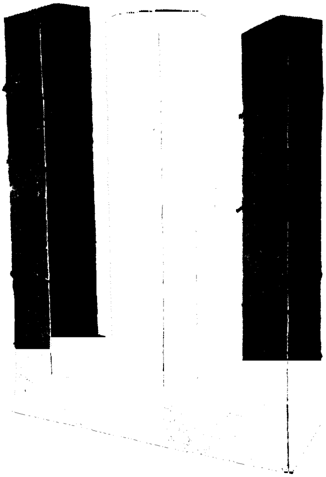


FIG 546

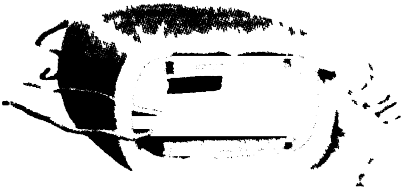


FIG. 548

FIG 547

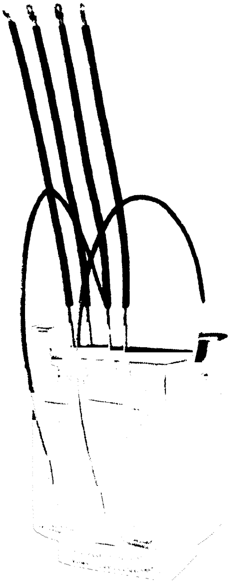


FIG 549

formers can be connected for use on three-phase circuits, as we shall learn later.

In general, transformers are built in one of two patterns:

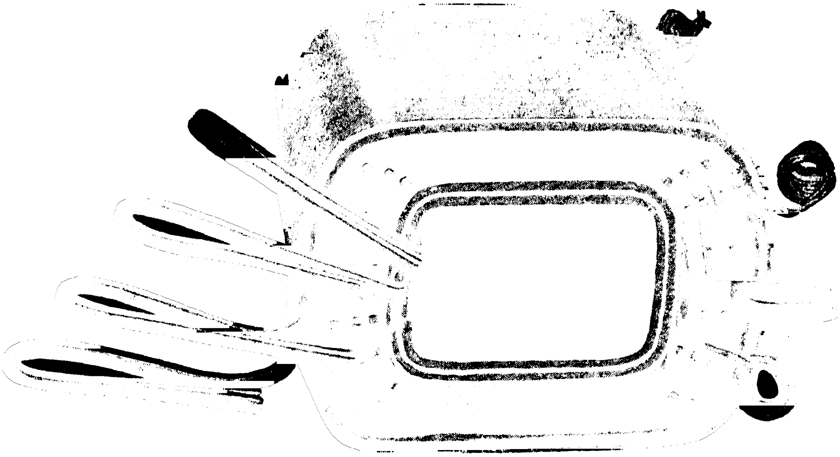


FIG. 550

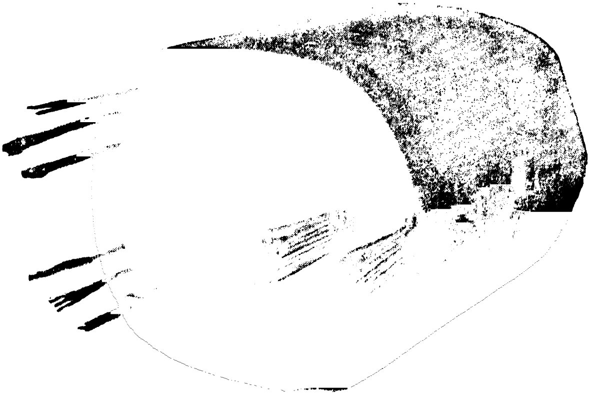


FIG. 551

the "shell" type and the "core" type; and for one of two general purposes: the smaller as "distribution" transformers, the larger, as "power" transformers used in connection with central stations or sub-stations. Fig. 540 shows a Wagner

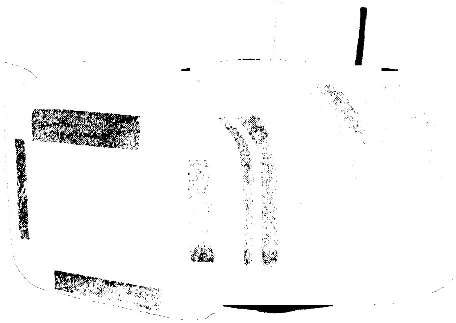


FIG. 552

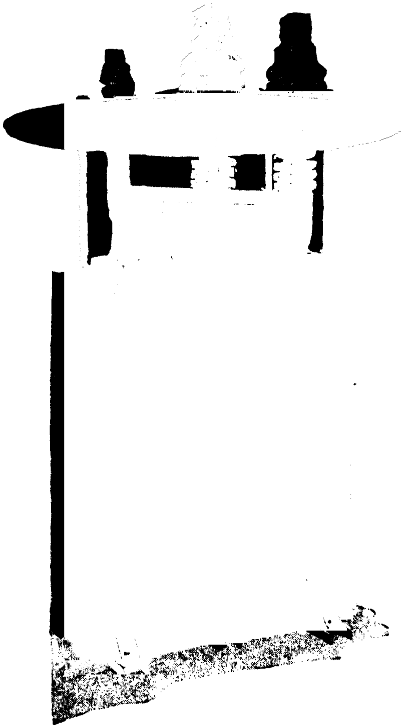


FIG. 553

oil-filled self-cooled "power" transformer designed for 2,000 Kva. and 66,000 volts. Fig. 541 shows three Kuhlman distribution transformers, the one at the top having a rating

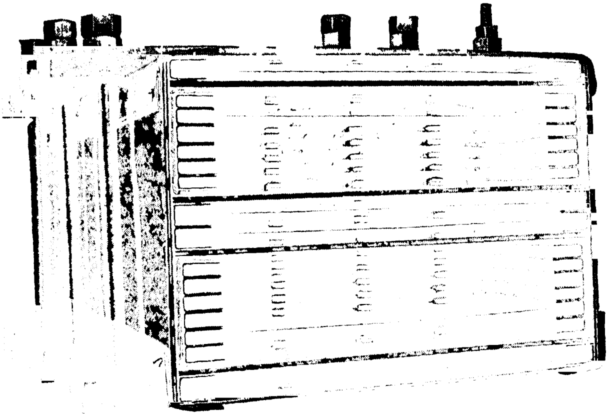


FIG 551

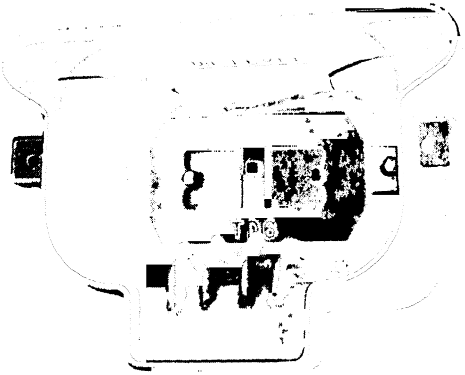


FIG. 555

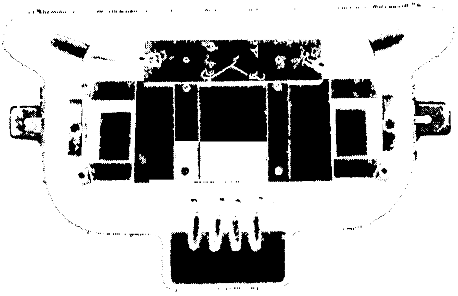


FIG. 556

of 15 Kva. and stepping the voltage down from 4,800 to 120 and 240 volts.

Fig. 542 illustrates the shell type of construction, while Fig. 543 shows the three-phase core type. In the shell type the coils seem to be inclosed (partially at least) by the laminated steel core, whereas in the core type the coils partially inclose the core. Figs. 544, 545 show modified cruciform-core types. For larger capacities and very high voltages (6,600

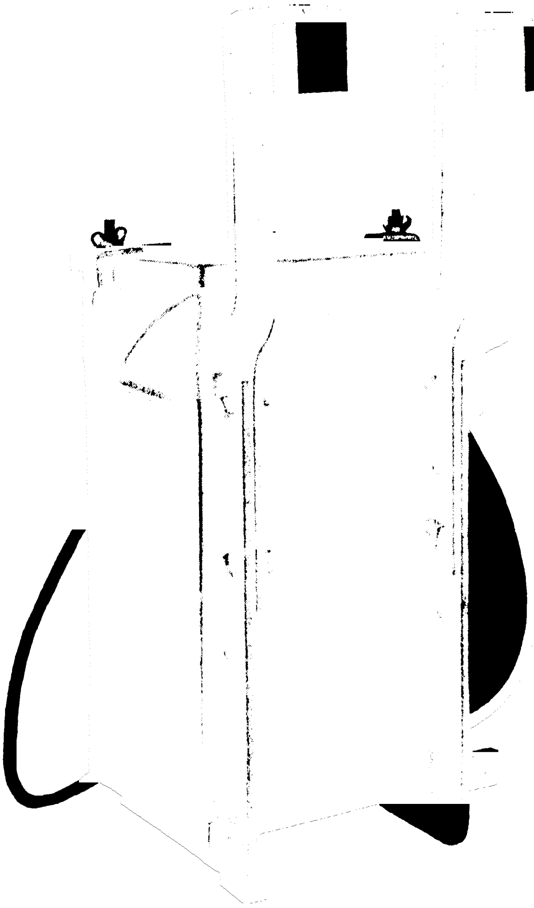


FIG. 557

and above) the core type of construction seems to be more common.

Transformer cores are built out of high-grade magnetic steel (silicon steel). Cores are laminated as shown in Figs.

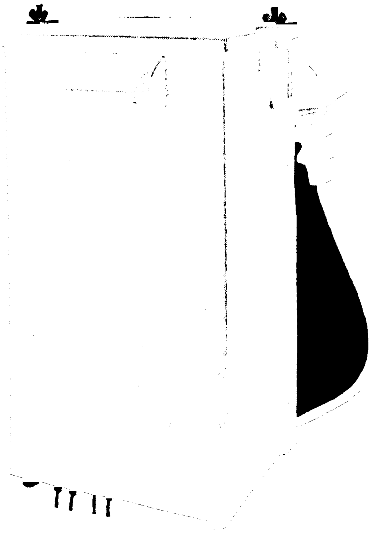


FIG. 558

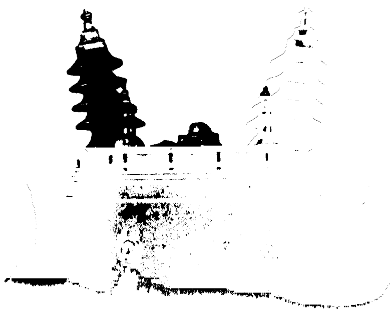


FIG 559

546, 547. The latter shows the cast-iron base, the completed coils, and a partially assembled core.

Coils are circular or rectangular in shape, the former being preferred for the higher voltages. The low-voltage coil is

FIG. 560

placed next to the core, but is well insulated from it. The high voltage coil is placed outside the low voltage coil and is separated from it by suitable insulation. See Figs. 548, 549. Occasionally half the low voltage coil is wound outside the high voltage coil. See Figs. 550, 551. For very high voltages, however, the low voltage coil is next to the core and the high voltage coil is built into layers or units as shown in Fig. 552. Observe in these pictures and in some following the liberal spaces provided for ventilation or for oil circulation.

In some types of transformers, both coils are wound in "pancake" layer fashion and then are "interleaved" around the core. Such construction is shown in Figs. 553, 554. Magnetic leakage is reduced in this type of construction.

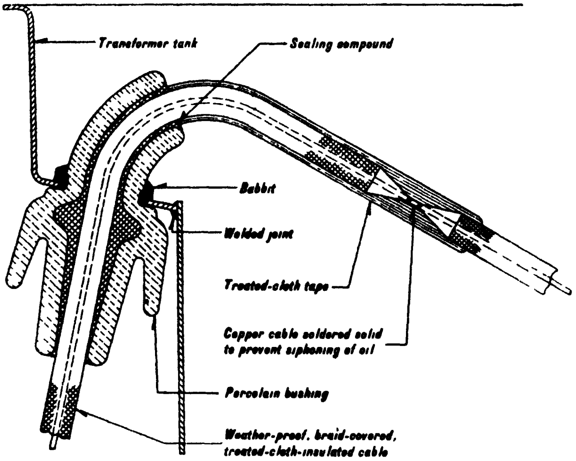

Transformer tank
Sealing compound
Babbit
Welded joint
Treated-cloth tape
Copper cable soldered solid to prevent siphoning of oil
Porcelain bushing
Weather-proof, braid-covered, treated-cloth-insulated cable

FIG. 561

One other important construction feature regarding transformers must be mentioned. It concerns the leads from the coils through the case to the outside. Since these leads are at a high potential difference, a great deal of attention must be paid to the methods of insulating them from the case.

Observe in Fig. 555 how leads are brought out in the case of transformers whose voltages range about 2,300-4,600 volts. Figs. 556, 557 show the types of bushings used for the low-voltage and the high-voltage leads respectively. Fig. 558 shows the high-voltage bushing on a transformer in the 6,900-13,800 volt class, while Fig. 559 shows a "petticoat" bushing on a transformer whose primary voltage is above 14,000 volts. Such a petticoat bushing is shown separately in Fig. 560. A further illustration of the character of the lead and the bushing for a 6,900 volt transformer is given in Fig. 561. For extremely high voltages, a condenser type of bushing is used.

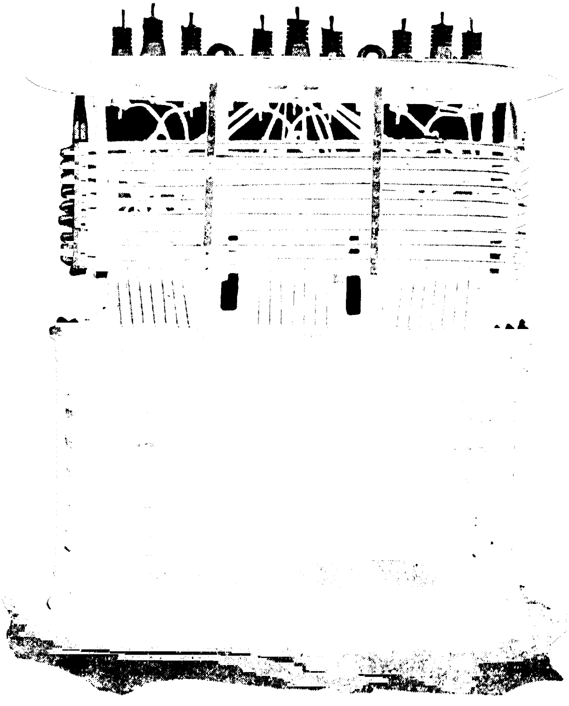


FIG. 562

91. COOLING:

Transformers of very small capacity and built for special purposes may be without any special provision for cooling other than that afforded by ventilation given by circulating air currents. Ordinary power and distribution transformers are cooled usually by oil or by oil and water. Air or air blasts have in general proved objectionable.

Fig. 562 shows an oil-insulated water-cooled three-phase transformer. The copper tubing at the top carries circulating water. The heated oil surrounding the coils rises to the top of the case, where it is cooled by contact with the copper tubes. The surface of the transformer case is usually smooth in this type.

Oil-cooled transformers (except small capacity) usually have corrugated surfaces to permit more rapid radiation of heat to the outside air. See Fig. 563. In some forms, pipes welded into the side of the transformer case or radiators fastened on the side of the case permit circulation of the cooling oil and multiply the cooling surface.

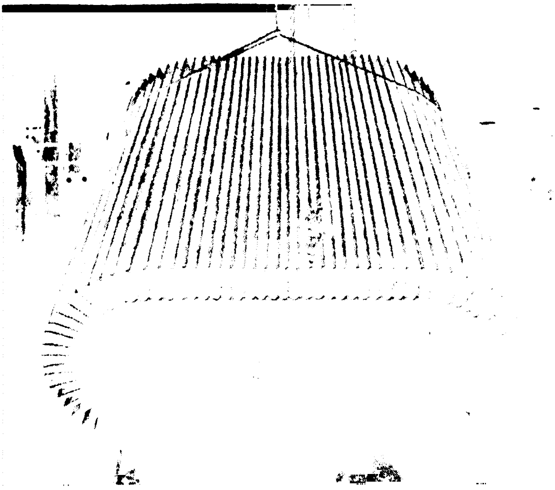


FIG. 563

The transformer oil must be well chosen for its insulating qualities. It may not contain moisture and must be renewed at intervals. Provision for the exclusion of moisture is made, especially for the larger transformers, by use of a "breather" arrangement (see Figs. 564 and 564A), or by means of an expansion tank (Fig. 565). The former permits air to leave the transformer case as the oil and the air expand due to temperature rise. But upon cooling the air coming in through the breather has the moisture taken out of it by forcing it through calcium chloride or some other dehydrating compound. The expansion tank is an overflow tank. The oil in the transformer fills the case and overflows into the expansion tank above. When the oil expands due to temperature rise, the excess oil rises to the tank above, forcing out air. Cooling permits oil to go back into the case and air to be drawn into the expansion tank (also through some chemical). Thus no moisture gets into the transformer case.

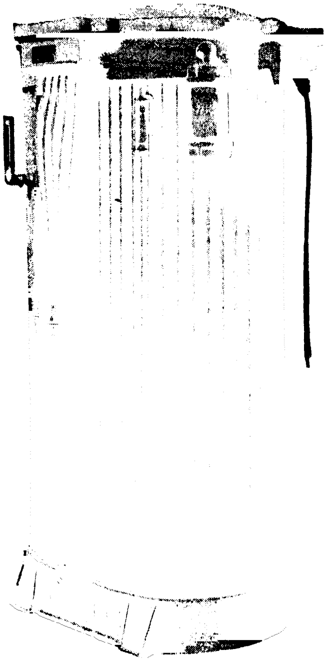


FIG. 564

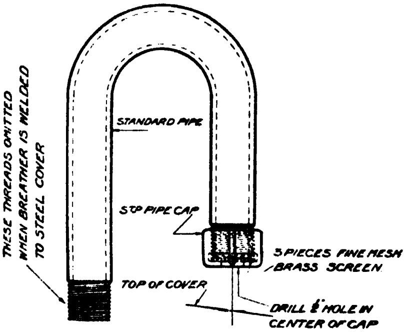


FIG. 564A

Oil deteriorates and with time a sludge appears. The oil must be drained off and renewed.

Where no special provision is made to exclude moisture, as is the case in smaller sizes, the transformer core and coils do not rest on the tank bottom. A space is allowed at the bottom for the accumulation of moisture, which can be drained off at intervals.

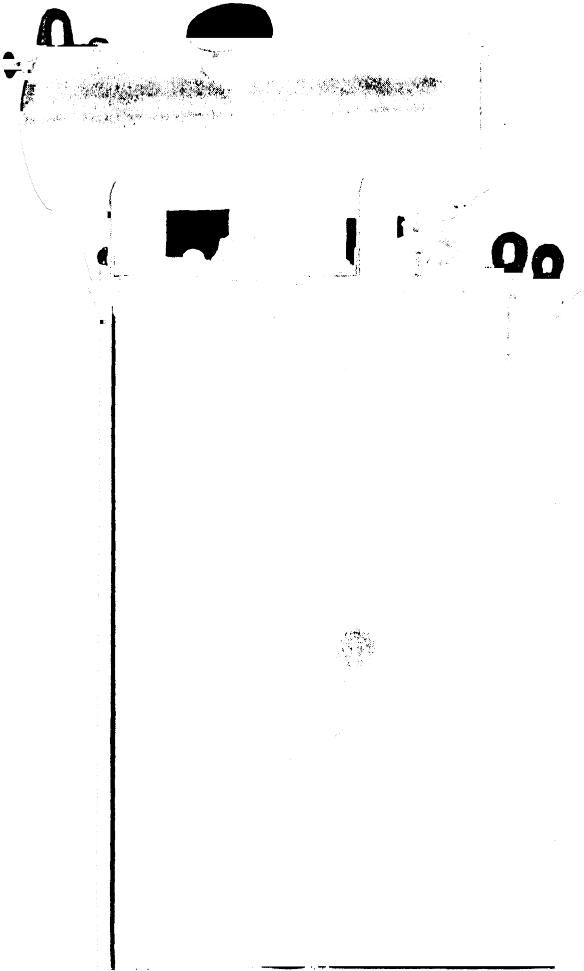


FIG. 565

92. TRANSFORMER POLARITY:

Transformer leads should be marked to indicate definitely the polarity. The letters H_1, H_2, H_3, are used for the high-voltage leads; X_1, X_2, X_3, are used for the low-voltage leads.

Thus in Fig. 566, the letters *H* and *X* indicate the high and low voltage leads respectively, but there should also be an indication as to the sense of the voltage in the two coils. Some manufacturers bring out the leads, marked as in Fig. 566, others mark them as in Fig. 567. In either case the polarity is such that when the voltage in the high-tension coil is from H_1 to H_2 the voltage in the low-tension coil at that instant is from X_1 to X_2. This means that when H_1 and X_2 leads are adjacent the two coils joined in series give an additive result, while if H_1 and X_1 are adjacent, a series connection of the two coils would show a subtractive effect. By impressing a *safe* (low) *voltage* on the high-tension side,

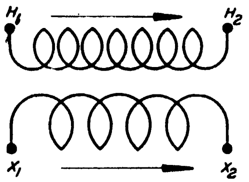


FIG. 566

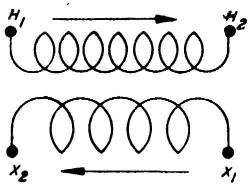


FIG. 567

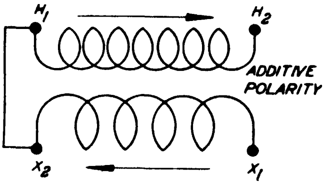


FIG. 568

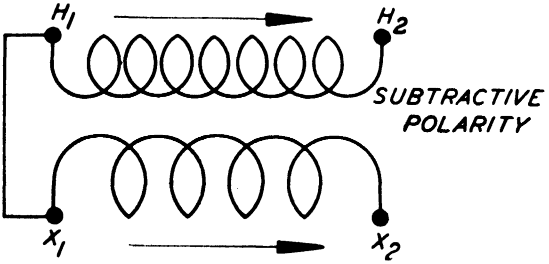


FIG. 569

and connecting as shown in the illustrations, this test can easily be made by the use of a voltmeter across the free ends of the coils (see Figs. 568, 569). Transformers should be marked "additive" or "subtractive" polarity as a further safety precaution.

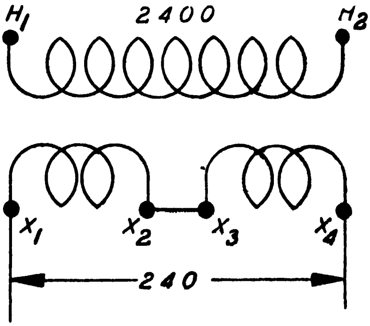


FIG. 570

93. TRANSFORMER CONNECTIONS:

There are very many ways in which transformers can be connected. Some are quite objectionable; others are commonly used. We shall confine ourselves here to those in more common use. It is common practice to divide the low-tension coil into two parts, and to bring out four leads instead of two. This makes possible two voltage ratios, one double the other,

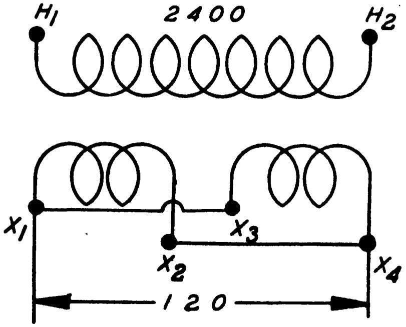


FIG. 571

because the two parts of the low-voltage coil can be connected either in series or in parallel as shown in Figs. 570,

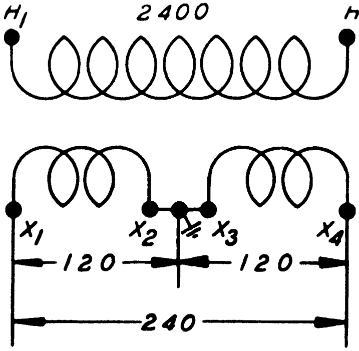


FIG. 572

571. The most common arrangement of connections for the single-phase transformer is the series for three-wire service

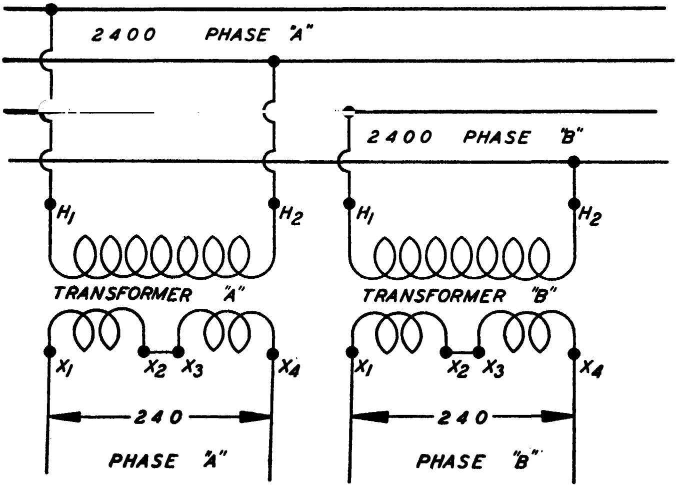


FIG. 573

to the consumer. See Fig. 572. The ratio is 10 : 1, but with the middle tap brought out to a middle or neutral wire, the voltage between either outside wire and the neutral is only

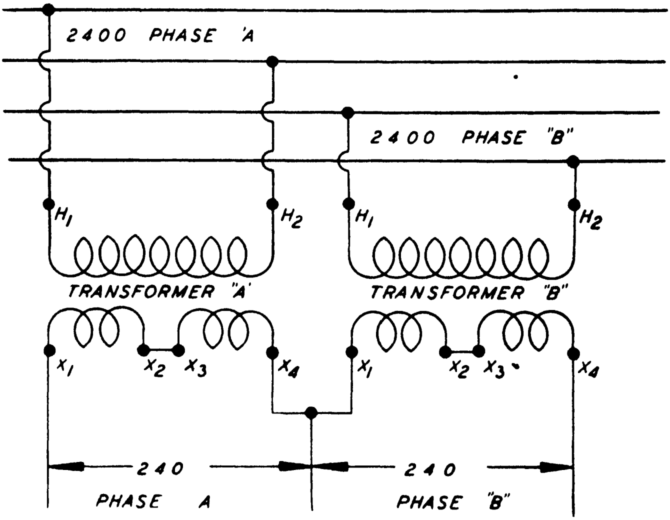


Fig. 574

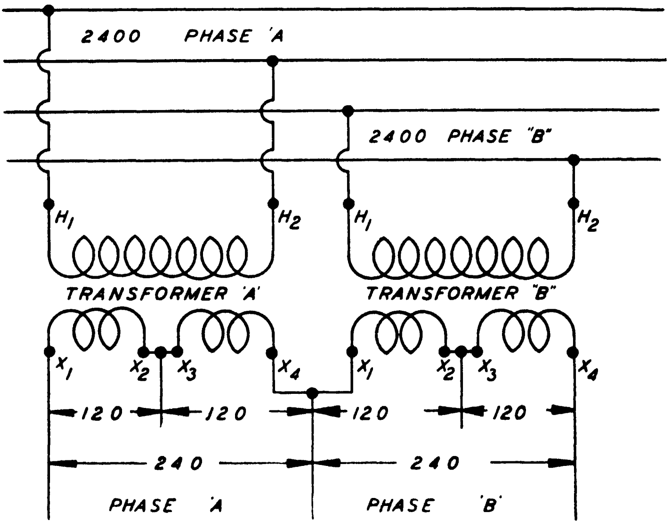


Fig. 575

half that between outside wires. This system is well adapted for light and power service, the 120 volts serving for the lights and the 240 volts for power, and is the system commonly employed in serving households. The neutral wire is grounded at the transformer.

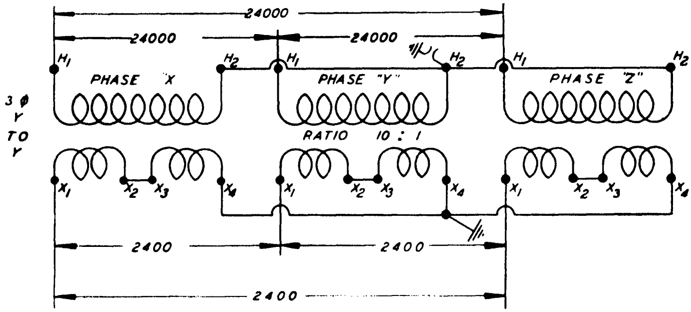


FIG. 576

Two single-phase transformers can be used for two-phase voltage transformation. Thus, assume a two-phase four-wire, 2,300 volt source, as in Figs. 573, 574, 575. The primary of each transformer is fed by one phase from the supply line.

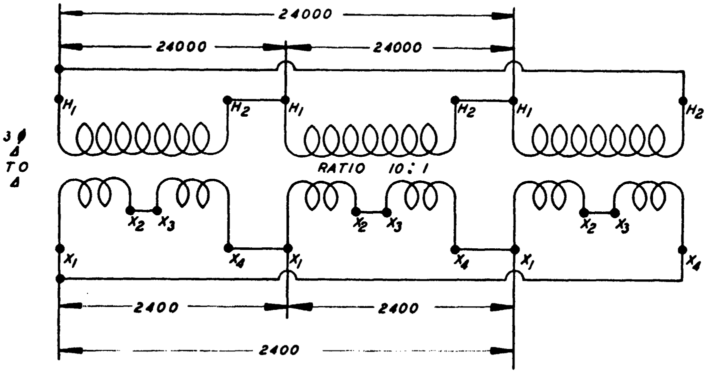


FIG. 577

The secondaries or low sides are arranged respectively for four-wire, three-wire, and five-wire, two-phase service. The neutral of one transformer may be grounded.

While two-phase equipment is still being used, it has been pretty well superseded by three-phase, and hence the three-phase arrangement of three single-phase transformers is far more common. For simplicity we shall show here only those

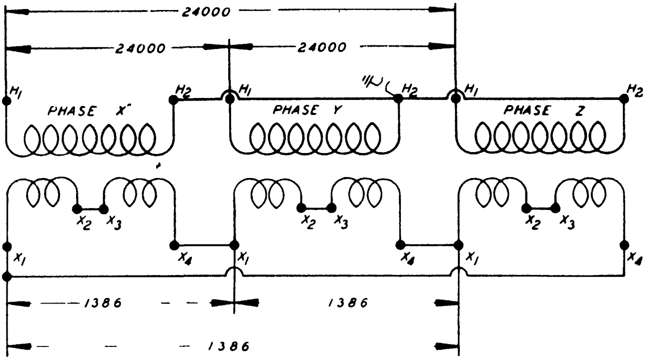


FIG. 578

connections which call for the low-voltage coil halves joined in series. Three single-phase transformers are preferable to a single three-phase unit of equal capacity, because of greater

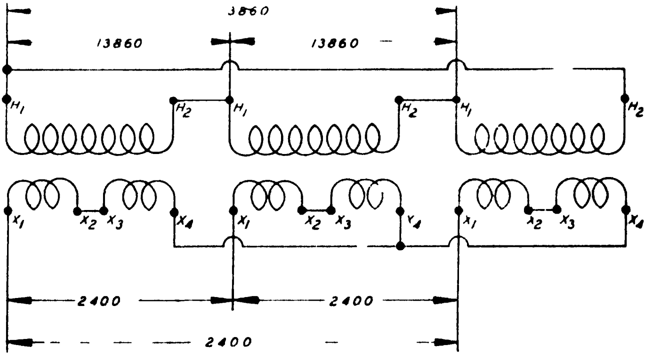


FIG. 579

accessibility when making repairs and less interruption to service, since it is possible to continue two transformers on open delta, while a third is being repaired. The star and delta connections are used on primary and secondary coils as well. Hence we may have primary connected in star, secondary in star; primary in delta, secondary in delta; primary in star, secondary in delta; primary in delta, secondary in star. These four arrangements are shown in Figs. 576 to 579 respectively.

The star-to-star connection requires a fourth wire if an unbalance of loads is to be prevented and this makes it somewhat objectionable for distribution of power to the consumer. But this connection is quite serviceable where high-voltage transmission lines of different voltages are being tied together into a common system. The common neutral point makes grounding very convenient.

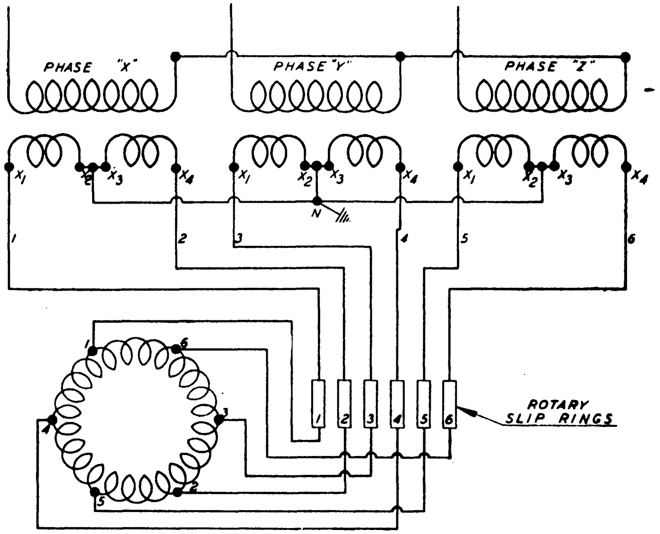


Fig. 580

The star-to-delta connection is a very common arrangement of transformers. The neutral of the primary permits convenient grounding, although to ground the secondary (delta) an artificial star might have to be arranged to secure a neutral. If single-phase currents are taken from the secondary side these should be distributed over the three "legs" to maintain a balance.

The delta-to-star arrangement while used for distribution is not as common as its converse just described. The delta-to-delta connection is quite desirable when transformers are banked in parallel, but it is not often used for distribution.

94. TRANSFORMATION FROM THREE-PHASE TO SIX-PHASE:

It is quite desirable to change three-phase service to six-phase in connection with rotary converters, as will be shown in the discussion on converters. This transformation can be made in several ways. That connection known as the "diametrical" seems to be in most common use. It is so called because the leads from each secondary feed the rotary converter at points in the rotary winding diametrically opposite each other. Fig. 580 shows this diametrical connection. The secondaries develop apparently only a three-phase voltage, but the manner of connection to the rotary is such as to produce a six-phase relationship in the rotary as shown in Fig. 581. The diametrical connection allows a convenient neutral

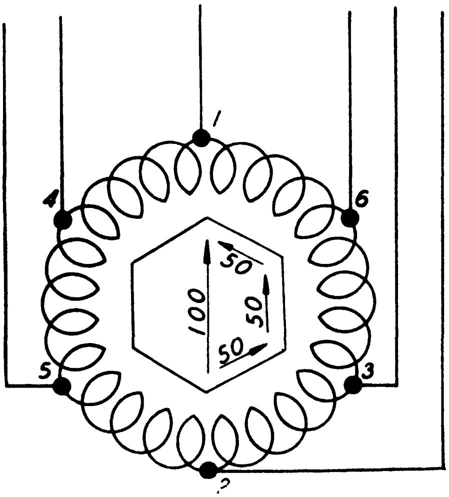


FIG. 581

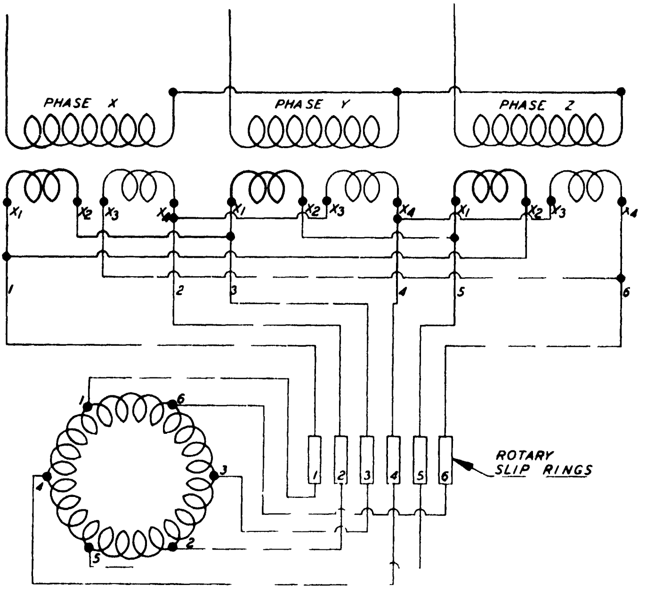


FIG 582

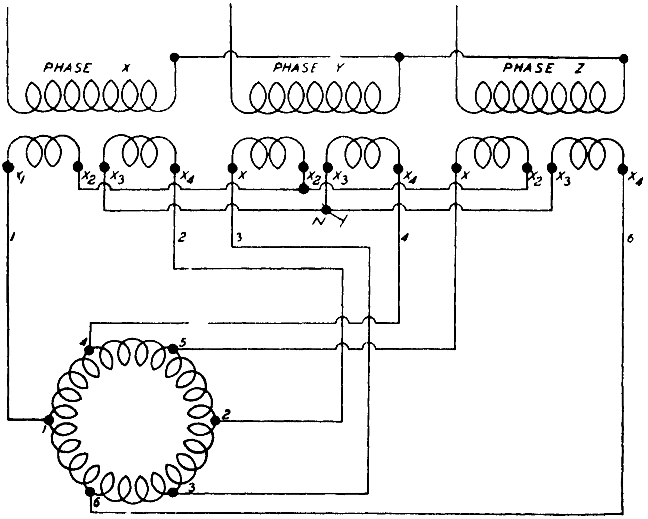


FIG. 583

for grounding as is shown by the dotted connection in Fig. 580.

Another fairly common arrangement for three-phase to six-phase transformation is the double delta. A secondary divided into two parts is needed for this connection. One half of each secondary is used for one delta, the other half of each secondary is used for the second delta. See Fig. 582. Note, however, that in one delta the secondaries are reversed with respect to the other. The leads from each delta are joined to points on the rotary 120° apart, the second delta being displaced 60° from the first.

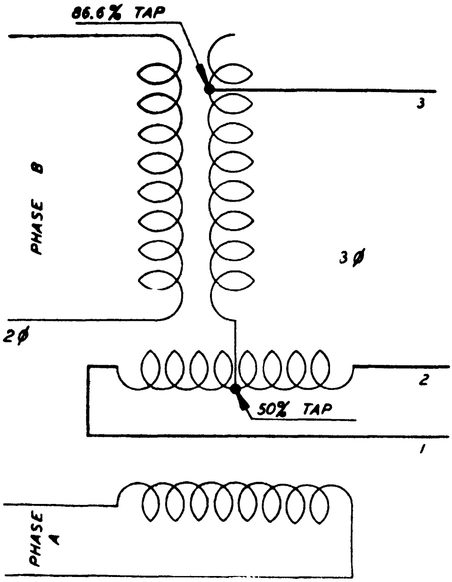


FIG. 584

The double-star connection is shown in Fig. 583. This is in reality the diametrical connection when the middle points of the secondaries are joined in a common neutral.

95. TRANSFORMATION FROM TWO-PHASE TO THREE-PHASE:

This connection is called the Scott connection, after its inventor; also the tee-connection, after the appearance of the wiring symbols. The Scott connection requires two single-phase transformers. Either one of two possible arrangements can be used. Fig. 584 shows the first of these. Phases *A* and *B* of the two-phase source are respectively connected to the primaries of the two transformers. The secondaries of the two transformers are themselves electrically joined so that one end of one secondary is connected to the middle tap of the other secondary as shown in the diagram. Moreover, the first of these secondaries must have an 86.6% tap available near its free end. Then the three-phase voltage terminals are points, 1, 2, 3, as shown, and the three-phase lines are connected at these points.

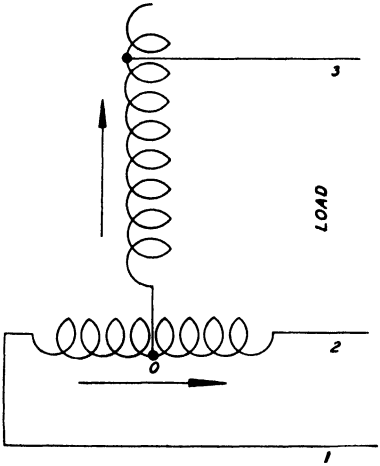


FIG. 585

Now let us see how the two-phase voltage is, in this manner, converted into a true three-phase voltage. Assume the voltages developed by the secondary coils to have the positive maximum values shown by the arrows in Fig. 585. Then the voltage between lines 1 and 2 is the voltage $E_{1\text{-}2}$ developed by the secondary coil directly across these lines. The voltage between lines 2 and 3 consists in part of half the voltage $E_{1\text{-}2}$

and in part of 86.6% of the voltage of the other coil or E_{0-3}. These two parts must be combined by vectors to get the voltage E_{2-3}. Shall we add or subtract these vectors? If we begin at line 2 and trace the path to line 3 through the secondary coils we find our path opposes in sense the voltage E_{0-2} and is in the same sense as E_{0-3}. Therefore, E_{0-3} and E_{0-2} are to be combined subtractively, with E_{0-2} reversed, which is done in Fig. 586.

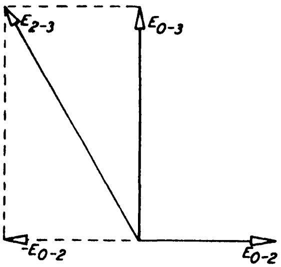


FIG. 586

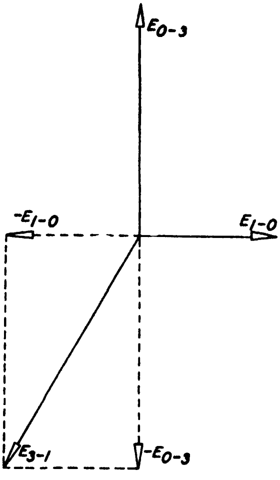


FIG. 587

Again, the voltage between lines 3 and 1, E_{3-1}, consists in part of E_{0-3} and in part of E_{1-0}. Beginning at line 3 and tracing the path, we find that our path is in opposition to the sense of the voltage, as indicated by the arrows, in both coils. Hence, both E_{0-3} and E_{1-0} must be taken negatively before combining by vectors. This is done in Fig. 587. Finally, the voltage between lines 1 and 2 is E_{1-2} or the voltage developed by the secondary coil which is across the two line wires 1 and 2. If we combine this voltage vector with the vectors E_{2-3} and E_{3-1} obtained in Figs. 586, 587, we find that these three line voltage vectors are 120° from one another. See Fig. 588. Moreover, we also find that the three voltages are equal. And it is to obtain three equal voltages that the 86.6% tap is taken. If the entire secondary were used, two of the voltages,

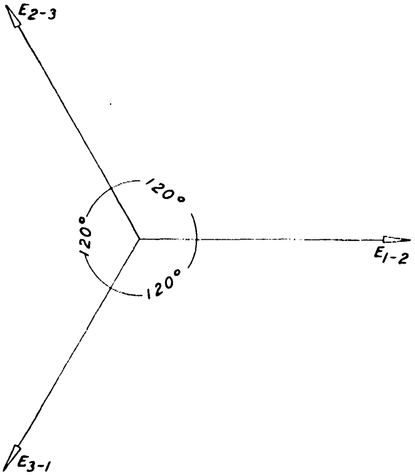


FIG. 588

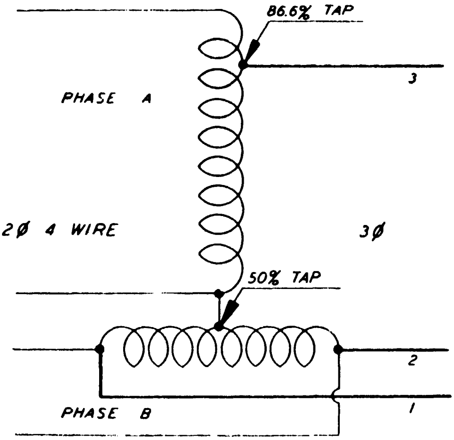


FIG. 589

E_{2-3} and E_{3-1}, would be too large. If 86.6% of the turns are used, E_{2-3} and E_{3-1} are exactly equal to E_{1-2}.

It is also possible to change from two-phase to three-phase by using only the one coil of each transformer for both primary and secondary. The wiring connections are shown in Fig. 589. This arrangement is really a combination of two auto-transformers, one of which has a 50% tap, the other, an 86.6% tap, available.

96. THE AUTO-TRANSFORMER:

The ordinary transformer has two coils: a primary and a secondary. We have already learned that the "compensator" used for motor starting purposes consists of a single coil, but makes use of the transformer principle. Here, a voltage impressed on the coil causes current flow, and also results in a counter-voltage. The latter can be used to furnish current to a load. In Fig. 590, a voltage is impressed on the whole coil *AB*. The back-voltage is almost equal to the impressed, since *R* for the coil is very small, and hence very little voltage is required to cause large current flow. In other words, *IR* is small but *IX* almost equal to 230. Hence, if a middle tap is available as at *C*, 50% of this back-voltage, or approximately 115 volts, is available for load service as for motor starting. Now this is actually a stepping down of the voltage from 230 to 115. If the number of turns taken between *B* and *C* included only 10% of turns, then the reduction of voltage would be from 10 to 1. In other words, the voltages are in the same ratio as the number of turns precisely as in

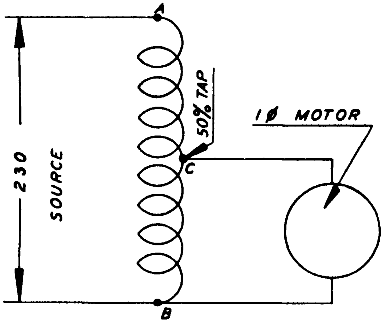


FIG. 590

the case of the ordinary transformer. Moreover, the current in this case is in reverse ratio to the voltage and hence also to the turns. As the voltage drops, the current rises in the same ratio. Fig. 591 will perhaps make this clearer. A 10-ampere input is transformed to a 20-ampere output into the motor. The portion *BC*, of the coil (secondary) contributes 10 amperes, and the line current 10 amperes, to total 20 amperes delivered to the motor.

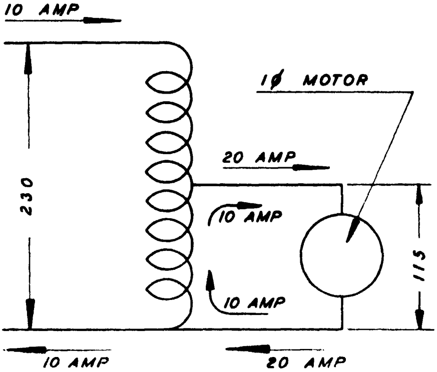


FIG. 591

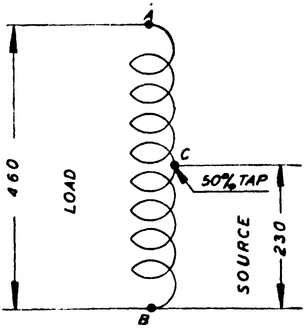


FIG. 592

The auto-transformer may also be used for stepping up the voltage (hence reducing the current) if desired. The connections are shown in Fig. 592.

Auto-transformers are very advantageous, particularly if transformation ratios are low. Aside from motor starting duty, the auto-transformer is used sometimes in central stations. Auto-transformers may also be connected in delta or star, the latter being much more common.

97. TRANSFORMER VOLTAGE REGULATION. VECTOR DIAGRAM:

Our discussions thus far have had to do with the constant potential transformer, it being understood that the load current is a variable quantity depending upon the need of the consumer at any time. Obviously, however, the consumer expects a constant voltage at the terminals of the transformer, which it is the business of the central station to supply. But a varying load current does have some effect upon the voltage available at the transformer terminals, so that "constant" potential does not necessarily signify an absolutely fixed potential, but one that varies not to exceed approximately 3%. Voltage regulation is defined as the percent change in voltage between no load and full load. If the rated secondary full-load voltage of a transformer is 230 volts, and the no-load voltage for this transformer is 238 volts, the difference between these values is 8 volts. This is 3.4% regulation, as shown below.

$$\frac{\text{No-load volt.} - \text{full-load volt.}}{\text{Full-load volt.}} = \frac{238\text{-}230}{230}$$

$$= \frac{8}{230} = 3.4\%$$

The voltage regulation of a transformer expressed as a percent, in itself means little, unless at the same time we state the power factor conditions of the load. Leading currents, lagging currents, and in-phase currents produce results on the voltage that correspond to the results which similar currents produce in the alternator. The student should remember that a transformer coil shows resistance and reactance effects. Hence there must be corresponding *IR* and *IX* voltage drops to push the load current through the secondary coil. As the load current changes, so too do *IR* and *IX*, and hence the terminal voltage varies with the load current.

It is interesting and instructive to construct the vector

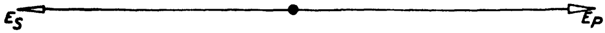


FIG. 593

diagram for the transformer. In Fig. 593, the two vectors E_p and E_s represent respectively the voltage impressed on the primary and the voltage induced by the secondary. These are of course, opposite in sense, or 180° E. apart in phase. If the secondary circuit is open (no load), the current I_e in

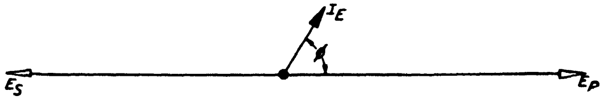


FIG. 594

the primary coil is small (less than 5% of the full-load current) and consists for the most part of exciting current or magnetizing current. It is, therefore, a current that lags by nearly 90° as shown in Fig. 594. Assume now that the secondary circuit is closed and that the load current I_s is an in-phase current. Then I_s lies on E_s as in Fig. 595. But I_s

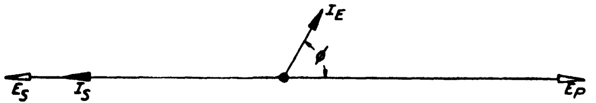


FIG. 595

itself has a magnetic effect, which opposes in part, at least, the magnetic effect of the primary current I_e. Now the current I_e is limited in size by the reactance effect of the primary coil. If something happens that reduces this reactance effect (or back-voltage) more current can flow into the primary. And this is just what happens when the secondary takes on current. The latter reduces the primary flux, which reduces the primary back-voltage (IX). Hence the impressed voltage is able to push more current into the primary. This it does until the effect of I_s in reducing the flux is offset by the effect of the increased current I_p in the primary. I_p, moreover, is opposite in sense to I_s and is so shown in the vector picture in Fig. 596, which also shows the total primary current I, the latter being $I_p \oplus I_e$.

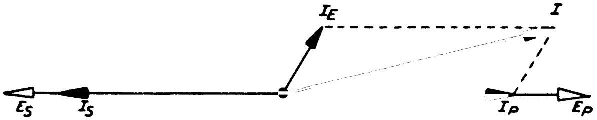


FIG. 596

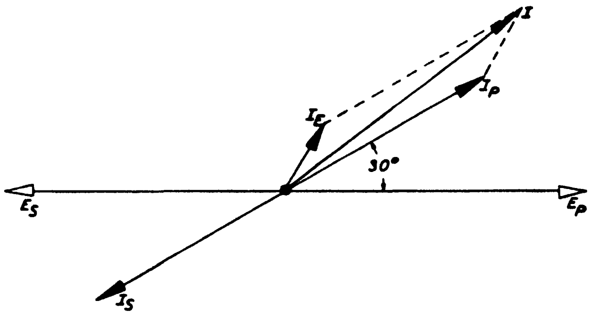


FIG. 597

If the secondary load current is lagging, say by 30°, I_p also lags by 30° and the vector picture is as shown in Fig. 597. These vector pictures all assume a ratio of 1 : 1.

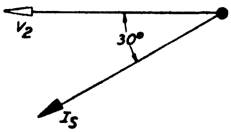


FIG. 598

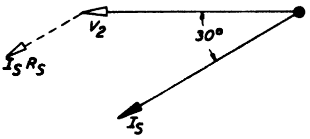


FIG. 599

It is also interesting and instructive to draw the vector diagram which shows the voltage drops IR and IX in relation to the impressed voltage and the load current. Let V represent secondary terminal voltage, E_p and E_s, impressed and induced voltages as before, and I_s secondary load current.

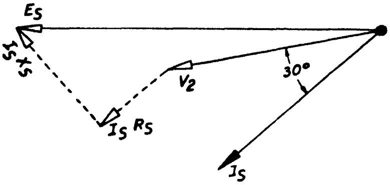


FIG. 600

We lay off I_s at the angle 30° (Fig. 598) assuming that the load current is a 30° lagging current. Then let us add to V_2 the I_sR_s drop across the secondary, as is done in Fig. 599. Note that this I_sR_s drop is parallel to (in step with) the

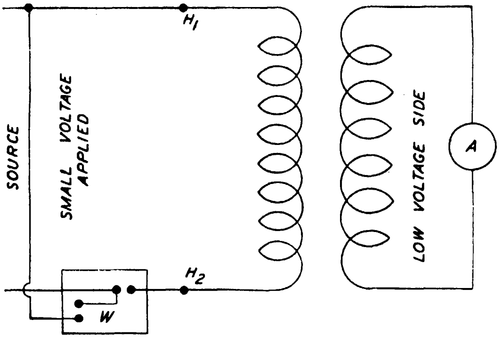


FIG. 601

current vector I_s. Also we add the voltage drop I_sX_s as in Fig. 600. Then $V_2 \oplus I_sR_3 \oplus I_sX_s$ together make up the total secondary volts induced, or E_s.

98. TRANSFORMER EFFICIENCY:

The transformer is one of the most efficient of machines. The losses in a transformer are due to the heating effect of the current in the coils (called copper losses), and due to the heat produced in the iron core by magnetic hysteresis and by eddy currents.

Copper losses can be calculated directly for different values of load, or for full load if the resistance of the primary and of the secondary coil is known. This loss in power is merely the I^2R loss in each coil for the given load current. The copper loss can also be measured by test. Usually the low-voltage side of the transformer is short-circuited and only enough voltage is supplied to the high potential terminals, to cause full-rated current to flow. See Fig. 601. This results in full-load current also in the short-circuited coil. A wattmeter inserted into the supply line will read the power input which is practically all copper loss under these conditions and for full load.

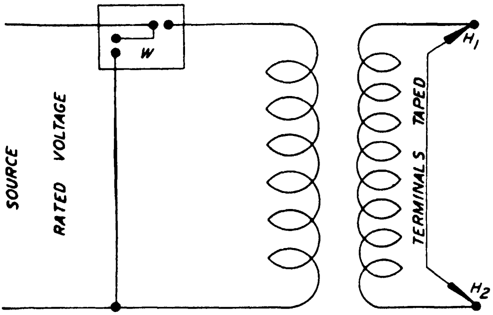


FIG. 602

The iron losses can be best determined by test. See Fig. 602. *The high potential terminals must be thoroughly taped to insure safety.* Full-rated voltage is then applied to the low-voltage coil. A wattmeter inserted into the line reads the power input, which under these conditions represents quite accurately the iron loss.

Knowing the copper and the iron losses it is easy to compute the efficiency for full load. We can compute or measure the power output or input and thus obtain the efficiency by the formula,

$$\text{Efficiency} = \frac{\text{Power output}}{\text{Power input}} = \frac{\text{Power input} - \text{losses}}{\text{Power output} + \text{losses}} .$$

Similarly, the efficiency can be determined for 25%, 50%, 75% loads if desired and an efficiency graph can be drawn. See Fig. 603. The iron losses are fairly constant at all loads; the copper losses vary according to load.

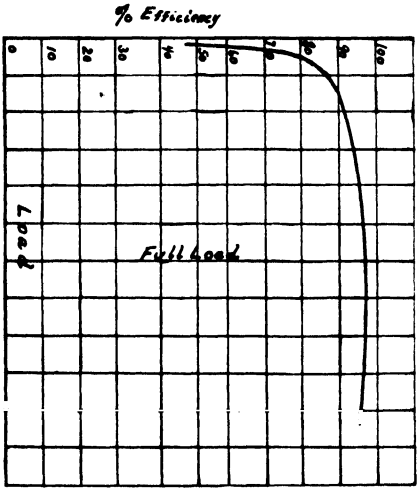
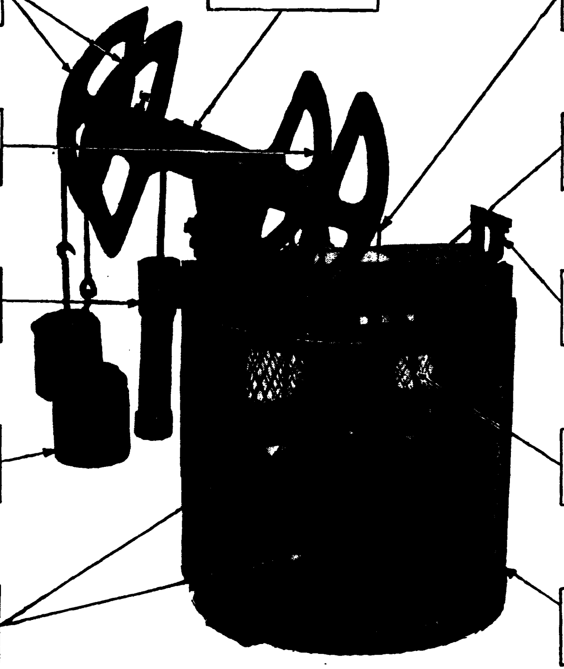


FIG. 603

99. SPECIAL DUTY TRANSFORMERS:

a) Street Lighting Transformers for street-lighting purposes are called "constant-current" transformers. We have discussed thus far, constant-voltage transformers. The construction of a constant-current transformer differs from the constant-voltage type particularly in that one or other of the two coils is movable. More often it is the secondary. Examine Figs. 604, 604A. Observe that the secondary coil is supported by cable which runs over a movable arm, and that the weight of the coil is balanced by counterweights at the end of the cable. The currents in the primary and secondary coils are, of course, opposite in sense, and hence the coils tend to repel each other. Being free to move, the secondary



Removable Sectors facilitate shipment. Parts removed when transformer is shipped.

Rugged Balancing Levers—For supporting coils and counter weights.

Dashpot—Of ample size to prevent swinging.

Accessible Balance Weights—Allow easy adjustment of current.

Sub-divided Windings—Light weight—Low internal voltages—Maximum ventilation.

Ball Bearings—eliminate friction.

High-grade Flexible Steel Supporting Cable.

Primary Connections—with extra tap for light load operation

Angle Iron Frame—Reduces weight, adds strength.

Special—Extra flexible leads to moving coil—Insures smooth operation.

Expanded Metal Casings—Permits inspection and prevents accidental contact with live parts.

FIG. 604

is thus able to vary its distance from the primary coil according to the load.

Lamps used for street-lighting are connected in series.

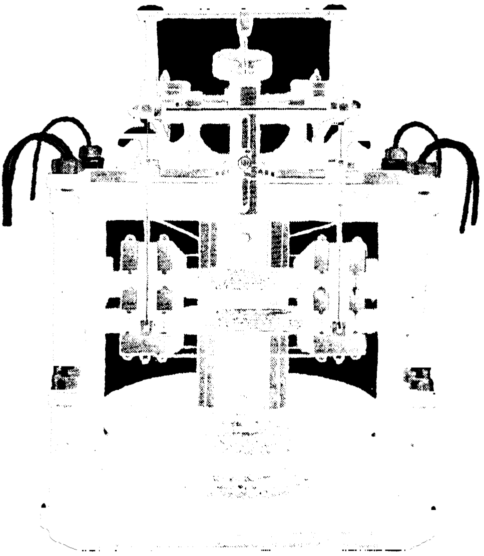


Fig. 604A

Hence a constant current is needed to maintain normal brightness. If one or more lamps should for some reason fail to operate, the circuit impedance is changed, and therefore

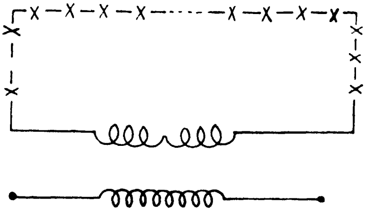


Fig. 605

the current would also vary if the secondary voltage remained constant. As the secondary moves away from the primary coil due to any tendency for the current to increase, there is less voltage generated in the secondary coil because of the increase in leakage of lines of force away from the secondary coil.

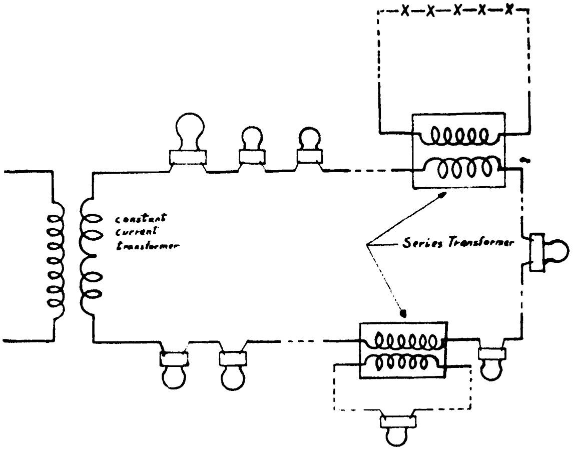


FIG. 605A

A constant-current transformer may supply a series of arc lamps directly as in Fig. 605, or it may supply current to several circuits by means of "series" transformers. These are so called because their primaries are joined in series with

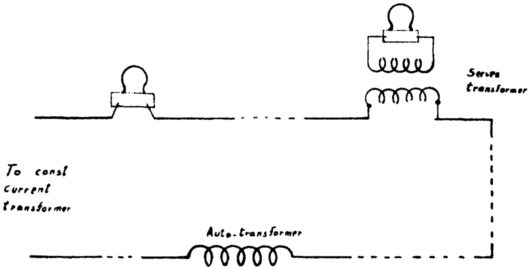


FIG. 606

the supply line just like an arc lamp. Fig. 605A illustrates this arrangement. Or again, the low-voltage series transformer may be used with each individual lamp as shown in Fig. 606, or even an auto-transformer can be used. In such cases the series transformer is placed in the base of the pole which supports the lamp.

b) Induction Voltage Regulator: This type of voltage regulator is not ordinarily classified as a transformer and yet basically it operates on the transformer principle. The purpose of a regulator is to maintain constant voltage on outgoing transmission lines or feeders. The impedance voltage (*IZ*) drop of feeders increases with load current. Hence some means of stabilizing the voltage is needed. Figs. 607, 608, show the essential parts (a stator with the secondary winding and a rotor with the primary winding) of an induction-type feeder voltage regulator. The connections are given in Fig. 609. Observe that the primary (rotor winding) is connected across the line, while the secondary (stator winding) is connected in series with the line.

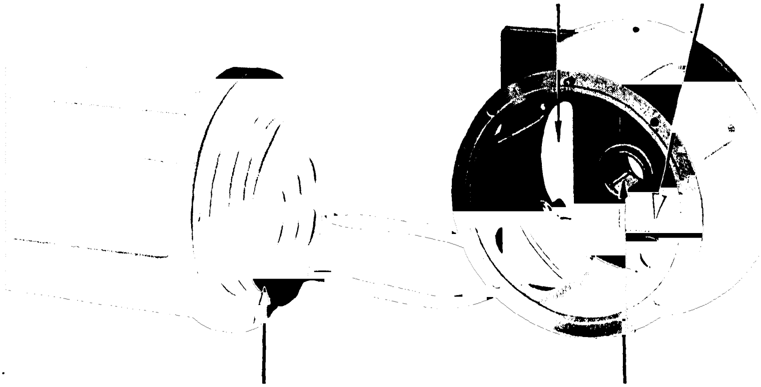


Fig. 607

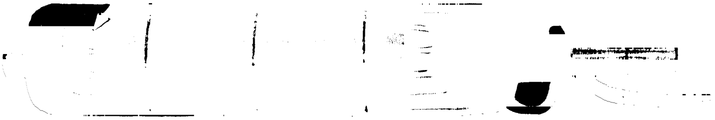


Fig. 608

Current flowing through the primary produces alternating flux. This flux linking itself with the secondary generates voltage. The number of volts developed depends upon the position of the rotor, which is free to move and is set either

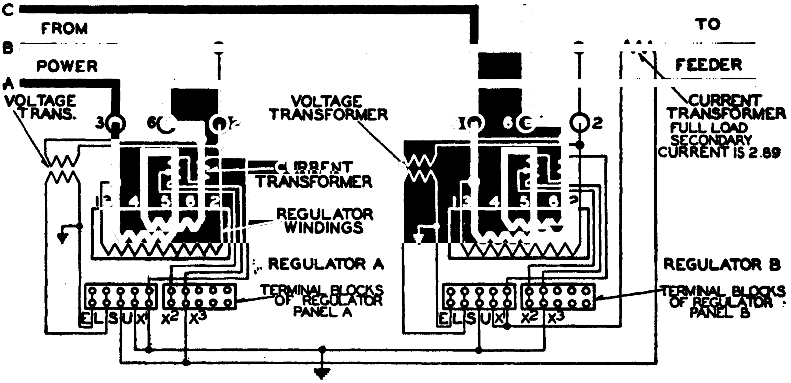


FIG. 609

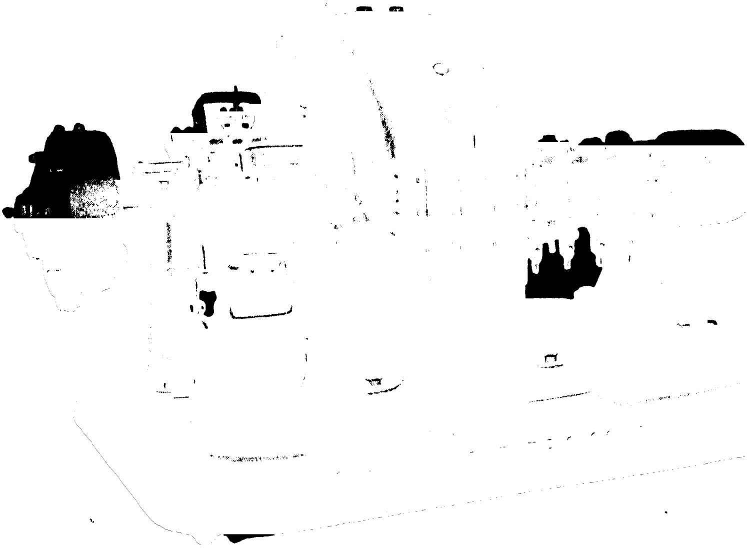


FIG. 610

by hand as in the manual type, or moves automatically through the use of relays and motor. As the feeder voltage decreases, the rotor shifts to a position which enables the secondary to generate a higher voltage. Because the secondary is connected in series with the line, the generated volts "boost" line voltage to the amount desired.

100. THE ROTARY CONVERTER:

This machine is built like a direct current shunt or compound motor. Fig. 610 shows a rotary converter, made by the General Electric Company. In addition to the commutator, a converter has slip rings, usually placed on the side opposite the commutator. Examine Fig. 611, which represents a two-pole direct current shunt motor. We know that the current in the armature coils is alternating in character. If, therefore, permanent taps be made in the winding and leads be brought to slip rings as is done in this illustration, an alternating current can be taken from the coils through the slip rings. This is precisely what happens in the single-phase alternator. Such an arrangement allows a variety of uses for the "rotary converter."

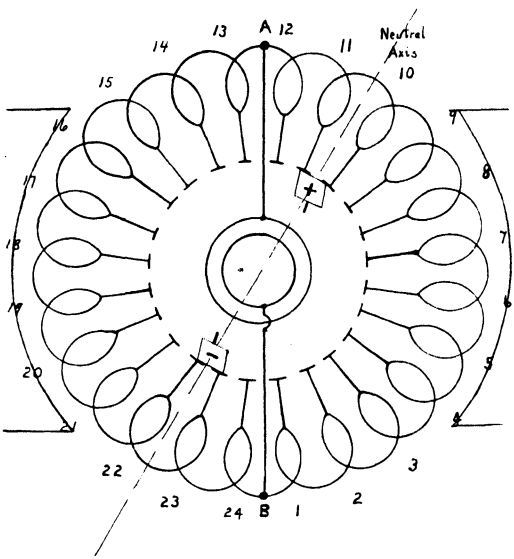


FIG. 611

a) Direct Rotary: Alternating current is fed into the winding through the slip rings, and direct current is taken out through the commutator.

b) Inverted Rotary: Direct current is fed into the winding through the commutator and alternating current is taken out through the slip rings.

c) Direct Current Generator: Mechanical power is used to rotate the armature and direct current is taken out on the D.C. side.

d) Alternating Current Generator: Mechanical power is used to rotate the armature and alternating current is taken out on the A.C. side.

e) Double Current Generator: Mechanical power is used to rotate the armature and both A.C. and D.C. are taken out simultaneously.

f) Synchronous Motor: The machine is operated as a motor from the A.C. side after it has been properly synchronized. The D.C. side is open.

g) Synchronous Condenser: The operation is similar to (*f*) but there is no mechanical load output; the machine merely floats on the line for purposes of power factor correction.

h) Direct Current Motor: Operation is from the D.C. side, with A.C. side open.

The chief use of the rotary converter is, of course, the first of these, namely, the conversion of alternating current into direct current. The arrangement thus far considered calls for two slip rings to which are fastened leads that come from taps taken exactly 180° E. apart on the armature winding. This is the single-phase arrangement. This winding may, of course, be tapped for two-phase, three-phase, four-phase, six-phase, or even twelve-phase operation. Six-phase is quite commonly used because of relatively greater power output capacity than the others. A study of the voltage and current ratios as between the A.C. and D.C. sides will help make this clear.

At the outset, let the student realize that a rotary converter is really a machine having one set of stationary field poles and one rotating armature; that the latter has only one winding which is tapped for commutator connections on one side, and for slip-ring connections on the other side; that the rotary in operation is running as motor and generator at the same time.

Again examine Fig. 611. There are twenty-four coils, twelve in each path. The voltage between taps *A* and *B* is the sum of the voltages developed by the several coils 1-12 or 13-24, the two sets being in parallel. Now each coil in the group 1-12 occupies its own position with respect to the center of the field pole. Hence the total voltage of the twelve coils is the vector sum of the twelve voltages taking into account their phase relationship. This is done in Fig. 612. Now suppose this total to be 100 volts. Then the single-phase voltage developed between slip rings is 100 volts. How does this compare with the voltage that exists at this time between the brushes on the D.C. side?

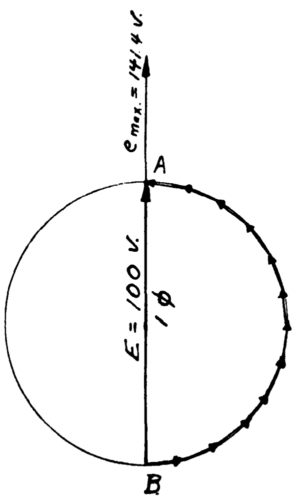


FIG. 612

Note in the first place that when the permanent taps to slip rings are in the position shown in Fig. 611, all of the coils in each path induce voltage in additive series. This position corresponds to the maximum voltage value of the cycle. When the taps reach the position shown in Fig. 613,

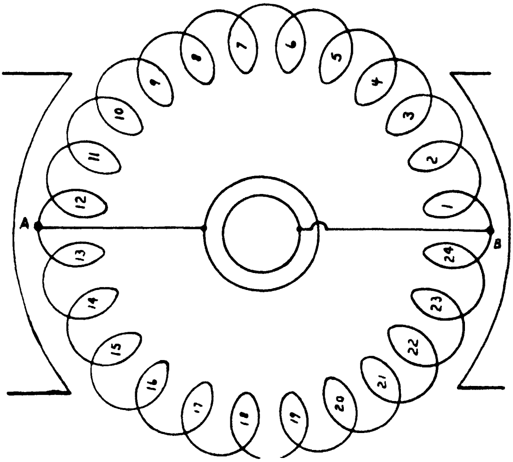


Fig. 613

half the coils in each path induce voltages opposed to those developed by the other half. Hence at this moment the voltage between *A* and *B* or between slip rings is zero. See

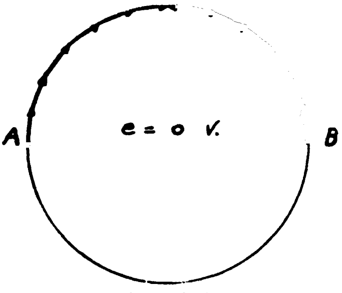


Fig. 614

Fig. 614. This position corresponds to the zero voltage value of the cycle.

This condition does not hold, however, for the D.C. side. The D.C. brushes always include between them in each path twelve coils in additive series. The voltage between D.C. brushes is therefore the maximum value. Moreover, it is maximum at all instants, since at all instants twelve coils in each path contribute their voltages in additive series. The condition that exists at the moment of maximum voltage between A.C. taps exists continuously as far as the D.C. brushes are concerned.

If then the effective single-phase A.C. voltage is 100, as was assumed previously, then we have only to determine the maximum value of such a voltage in order to find out what the corresponding voltage would be on the D.C. side. We recall that

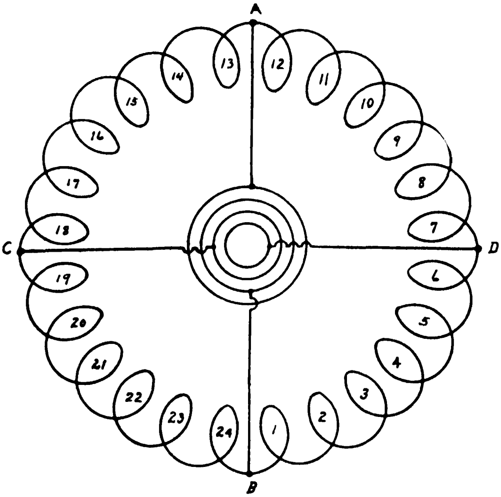


FIG. 615

$$E = .707\ E_{\max}$$

or $$E_{\max} = \frac{E}{.707},$$

from which $$E_{\max} = \frac{100}{.707} = 141.4 \text{ volts.}$$

We see then that 100 volts single-phase correspond to 141.4 volts on the D.C. side.

Suppose now that we tap the winding at *A*, *B*, *C*, *D*, as shown in Fig. 615. We obtain one phase *AB* developing 100 volts and a second phase *CD* developing 100 volts at 90° E. to the first. This arrangement permits a two-phase voltage, but since each coil is used in each phase, the current capacity per phase is reduced to one-half. Four slip rings and four line wires are necessary in this case. The winding is a closed winding and to attempt a three-wire system would result in short-circuiting the winding.

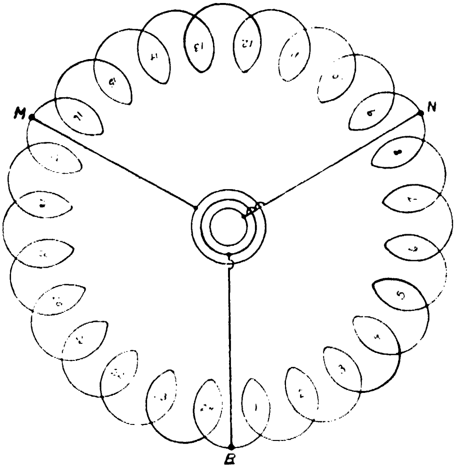


FIG. 616

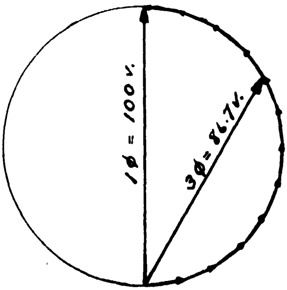


FIG. 617

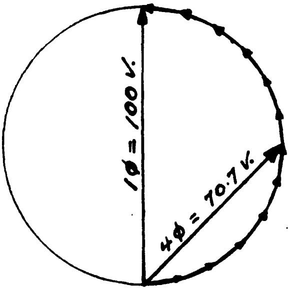


FIG. 618

If we desire to develop a three-phase voltage on the A.C. side, three taps taken 120° E. apart must be used. See Fig. 616.

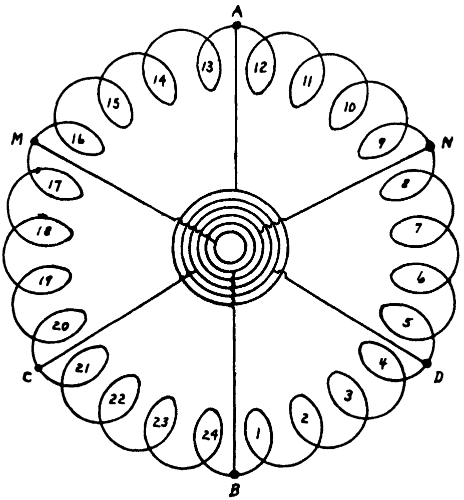


FIG. 619

The voltage between taps is the series effect of eight coils. Hence adding the eight effective voltage values by vectors as is done in Fig. 617, we find that the three-phase voltage

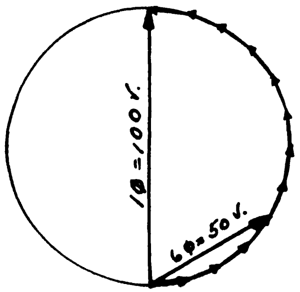


FIG. 620

corresponding to 100 volts for single phase is 86.6 volts.

For a four-phase voltage on the A.C. side the winding is tapped at four equidistant points just as in Fig. 615, but the phases are *AC*, *CB*, *BD* and *DA*. Now there are only six coils in each phase and of course there must be four slip rings. The voltage per phase as found by vectors is 70.7 volts. See Fig. 618.

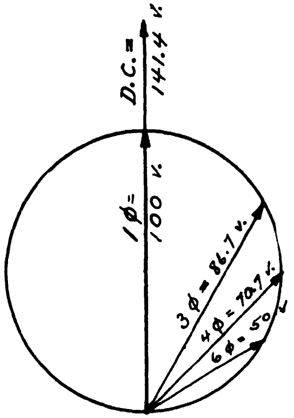


FIG. 621

Finally, the winding can be tapped at six equidistant points (60° E. apart) as is done in Fig. 619. Now there are only four coils per phase and the voltage per phase is 50 volts as obtained in the vector diagram, Fig. 620.

These results are summarized in Fig. 621, and also in the Table of Voltage ratios.

CORRESPONDING VOLTAGES AND VOLTAGE RATIOS

	Voltages	Ratio of D.C. to A.C.	Ratio of A.C. to D.C.
D.C.	141.4	....	....
1Φ	100.0	1.41	.707
2Φ	100.0	1.41	.707
3Φ	86.6	1.63	.612
4Φ	70.7	2.00	.500
6Φ	50.0	2.83	.353

As far as current relations are concerned it should be first remembered that since the rotary winding performs a double function, motor action and generator action, the current in any coil is really the difference between the amperes input from the line on the motor side and the amperes output into the line on the generator side. This is true because the output current and the input current are opposite in sense.

Suppose the winding to be tapped for single-phase, and that 100 amperes enter on the A.C. side at 100 volts. Assuming 100% efficiency and unity power factor for simplicity, we have

$$\text{power input} = \text{power output } (100\% \text{ eff.})$$

Then since 100 volts single-phase corresponds to 141.4 on the D.C. side, we have substituting

$$100 \times 100 = 141.4\ I_{d\text{-}c}$$

$$I_{d\text{-}c} = \frac{10{,}000}{141.4} = 70.7 \text{ amperes}$$

If we do likewise for the three-phase arrangement, and assume unity power factor and 100% efficiency we find that 70.7 amperes on the D.C. side correspond to 66.7 amperes on the A.C. side. Thus,

$$\text{power input} = \text{power output}$$

$$\sqrt{3} \times 86.6 \times I_{3\text{-phase}} = 141.4 \times 70.7$$

$$I_{3\text{-phase}} = 66.7 \text{ amperes}$$

For four-phase arrangements under similar conditions the A.C. current is 50 amperes, and for six-phase arrangements the A.C. current corresponding to 70.7 D.C. amperes at 141.4 volts is 33.3 amperes. These results are tabulated below.

	Corresponding Current	Ratio A.C. to D.C.	Ratio D.C. to A.C.
D.C.	70.7	....	.....
1Φ	100.0	1.414	.707
3Φ	66.7	.944	1.165
4Φ	50.0	.707	1.414
6Φ	33.3	.472	2.330

Another very interesting relationship is the power capacity for the same rotary converter when used for single-phase and for polyphase purposes.

	Corresponding Power	Ratio to D.C. Power Capacity
	Capacity Kva.	P.F. = 1.00 Eff. = 100%
1Φ	8.50	.85
2Φ	8.50	.85
3Φ	13.33	1.33
4Φ	16.40	1.64
6Φ	19.30	1.93
D.C.	10.00	1.00

The rotary converter may be started either from the D.C. or the A.C. side. In the former case, a D.C. starting-rheostat is used just as for a D.C. motor. The rotary is then synchronized with the A.C. source just like an alternator.

When started from the A.C. side, the A.C. line current produces a rotating flux in the armature similar to that in an A.C. motor stator. This flux causes currents to be induced in the field windings as also in the pole structure itself, thus developing torque sufficient to begin rotation. Reduced A.C. voltage is applied to the armature to prevent injury to field coil insulation due to high voltages generated. As synchronous speed is approached, full voltage is applied and the D.C. field circuit is closed. Should the D.C. polarity be wrong, the armature will not rotate under truly synchronous conditions but will take abnormally large currents accompanied by sparking. This condition can be corrected by reversal of the D.C. field current for a time long enough to allow for "slip" equivalent to one pole.

PROBLEMS—CHAPTER X

1. **A 2400/240 volt transformer has 2,000 turns in the primary (high-tension) coil. How many turns must there be in the low-tension coil?**

2. Assume that when the transformer in Problem 1 is carrying full load the low tension voltage drops to 232 because of the impedance voltage drop in the transformer coils. How many turns would have to be added to the secondary coil to make up for this voltage drop?
3. A single-phase transformer is rated at 100 Kva., 2,400/240 volts. What is the full-load current rating at unity power factor and 98% efficiency?
4. If the transformer in Problem 3 takes an exciting current of 4%, how many amperes does this represent?
5. Make a wiring diagram showing the high-tension coil of a transformer connected to a 2,400 volt supply line. The two parts of the low-tension coil are joined in series. Show this also and indicate a three-wire line to the load. If the ratio is 10 : 1 what are the voltages between line wires on the low side?
6. Repeat Problem 5 with the two parts of the low-tension coil joined in parallel.
7. Draw the wiring diagram showing three single-phase transformers connected $\triangle \triangle$, low sides in series. Assume 2,400 volts on the high side and 10 : 1 ratio. Indicate voltage between line wires on the low side.
8. Repeat Problem 7 for $\triangle$ Y connection.
9. Repeat Problem 7 for Y $\triangle$ connection.
10. Repeat Problem 7 for YY connection.
11. Repeat Problem 8 for two parts of low-side coil joined in parallel.
12. Repeat Problem 9 for two parts of low-side coil joined in parallel.
13. Suppose the power factor of the exciting current in Problem 4 is 0.12. How much power input does the exciting current represent?
14. The transformer in Problem 4 showed the following data on test: Open circuit (high side), Readings on low side: $E = 240$, $I = 16.8$, $P = 560$ watts core loss. Short-Circuit (low side), Readings on high side: $E = 80$, $I = 14.2$, $P = 848$ watts. Determine the efficiency at full load, assuming unity power factor.
15. If the copper loss at half-load and quarter-load are respectively 220 watts and 60 watts, what are the efficiencies under these conditions, assuming unity power factor.

CHAPTER XI

ELECTRIC POWER DISTRIBUTION

101. ELECTRIC POWER TRANSMISSION:

Production of voltage, current, and kilowatt-hours is only part of the power company's job. Power must be brought to the customer. To supply the consumer's demands in the city, the suburb, and the farm it is necessary to transmit power over greater or lesser distances. Economic distribution calls for transmission at high voltages with accompanying equipment such as poles, insulators, etc., and also local distributing stations called sub-stations. Reference is here made to Fig. 622A which attempts to picture schematically a distributing system.

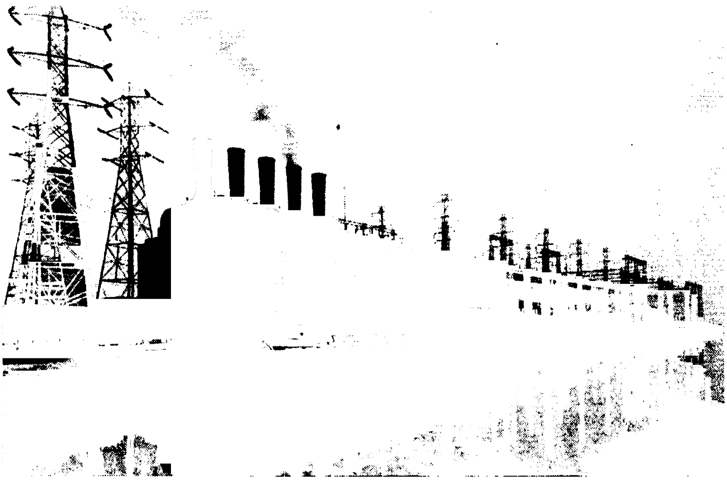


FIG. 622

Power is transmitted at different voltages depending upon distance, local conditions, overhead, or underground distribution, etc. Many cities prohibit overhead transmission lines within certain areas.

102. UNDERGROUND TRANSMISSION:

The depth of underground cables below the surface varies somewhat according to geographical location, but the aim is to keep below the frost line. Cables are not placed directly in the ground but in some form of conduit or duct which itself is embedded in concrete.

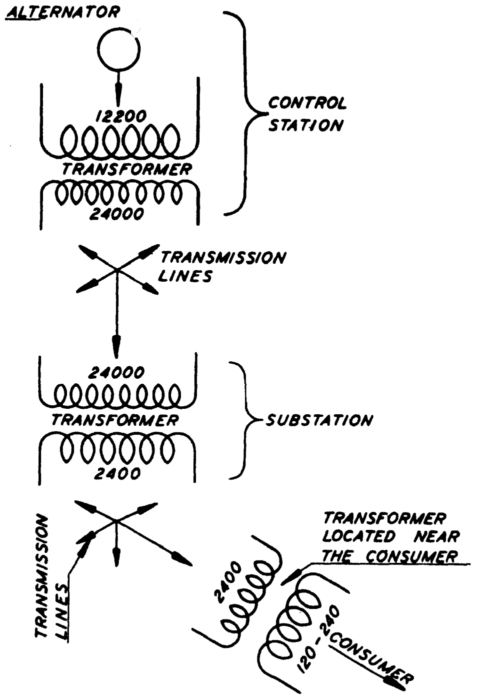


FIG. 622A

Conduits for underground purposes are made out of different materials and in different lengths. Some are round, some square, others octagonal. There are single-tube and multiple-tube (2, 3, 4, 6, 8, 9) conduits.

One type is made of wood. The outer walls are square, a circular hole being bored through the center. The lengths vary from 2 to 8 feet. The inside diameter varies to accom-

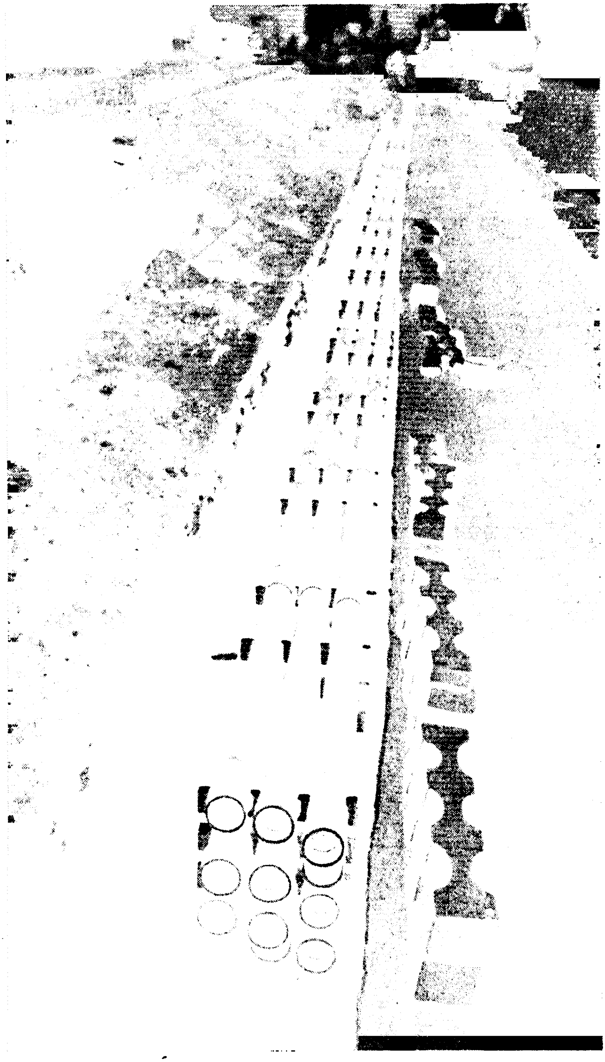


FIG. 623

modate different-size cables. Coupling of these tubes is made possible by turning down one end to a circular shape and by recessing the other end, producing a sort of socket type of joint. Yellow pine and Norway spruce are the chief woods used and saturation of the wood with creosote is the preserving process.

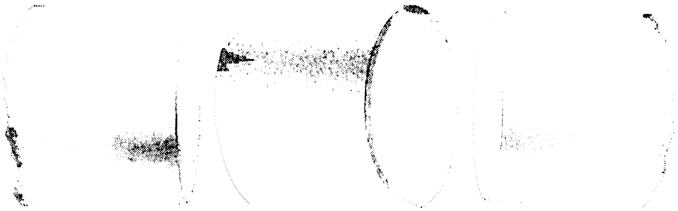


FIG. 624

Another single-tube type (Fig. 623) is made of wood pulp. A tar compound impregnation makes it thoroughly water proof. This duct is known as Orangeburg Fibre Conduit. Coupling is effected either by tapering both ends and slipping into a double tapered sleeve (Fig. 624), called a Harrington type joint, or by a socket-type joint shown in

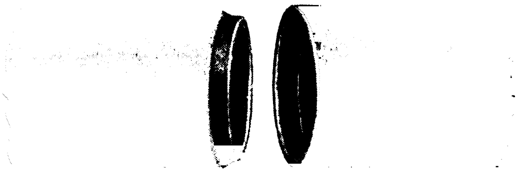


FIG. 625

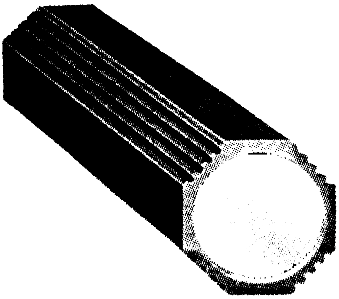


FIG. 626

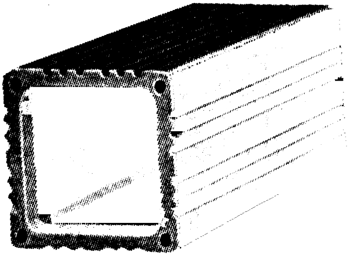


FIG. 627

Fig. 625. Assembling is completed by pouring hot tar over the joints to keep out moisture.

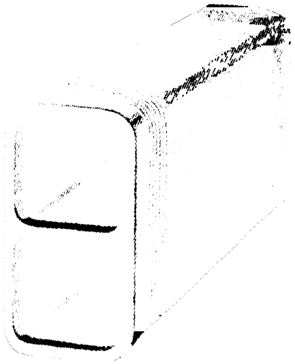


FIG. 628

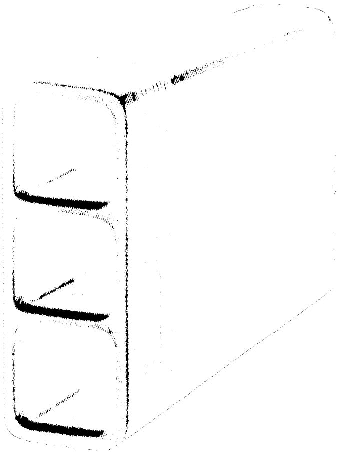


FIG. 629

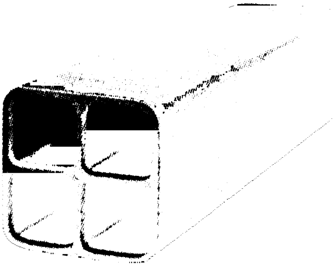


FIG. 630

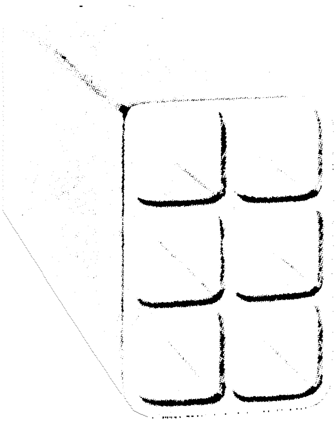


FIG. 631

Concrete tubes, with varying inside diameters, round in shape, 3 feet in length are sometimes used. Coupling is by butt joint with a steel ring over the joint.

Vitrified tile is also used for underground cables. Single and multiple tube tile are available, with circular or square inner bore. Single tubes are 18 inches long, multiple tubes from 24 to 36 inches. The illustrations in Figs. 626-32 show "Velveduct" clay tile made by the Clay Products Company. Coupling is made by butt joint. Steel dowel pins are used to align the ducts. Several thicknesses of cloth (Fig. 633) saturated with cement are placed around the joint.

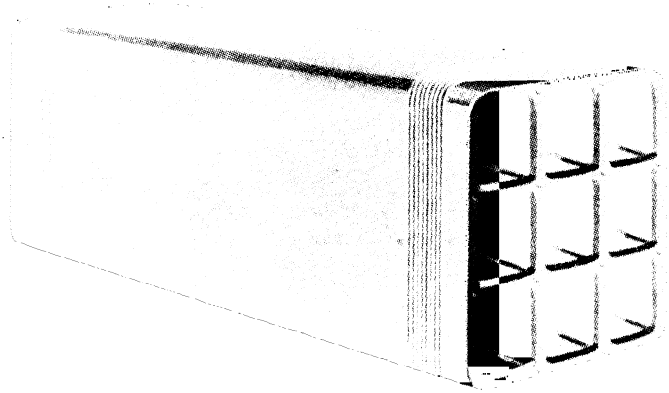


FIG. 632

Bends in underground lines require special care because they add greatly to the difficulty of drawing in the heavy cables. Single tubes and multiple tubes for 45° or 90° bends (shown in Fig. 634) are available. But these bends are of necessity long to offer as little resistance to cable pulling as possible. Sharp bends and branching of cables are done in a manhole.

With the exception of the wooden ducts, underground conduits are usually embedded in concrete. See Figs. 635-37. The wooden conduit is placed directly in the ground.

Conduit lines may be short or they may run underground for miles. Cable lengths are limited from the point of view of difficulty encountered when drawing into ducts, and convenient location of manholes. Cable splices may only be made in the manhole. The splice is too bulky to permit insertion into the conduit. Manholes are underground chambers made of brick or concrete, located under the road-bed.

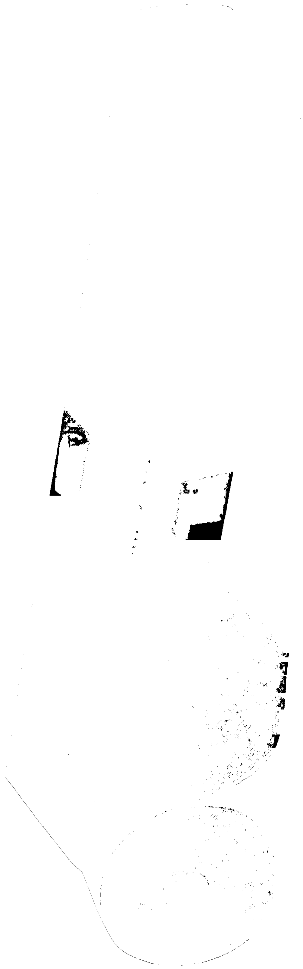


FIG. 633

The entrance to the manhole is round and is at the top of the chamber. The manhole cover closes the entrance and is flush with the road surface. Distribution transformers

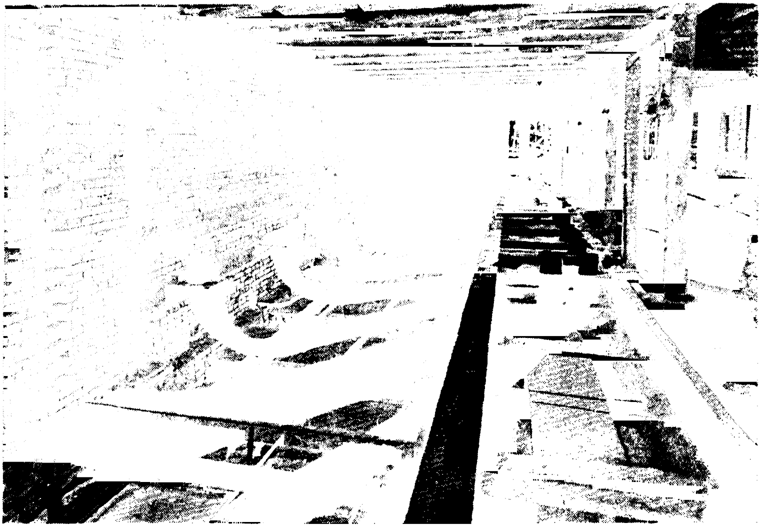


FIG. 634

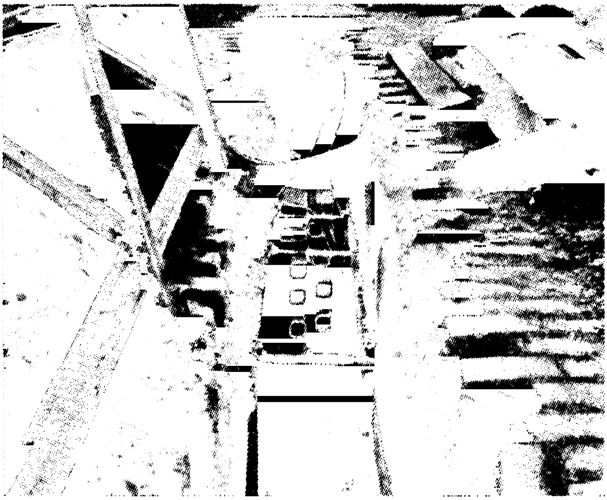


FIG. 635

are sometimes located in manholes. Distance between manholes depends on size of cables, lengths of street blocks, etc.

Drainage must be provided to keep the manhole reasonably dry. Holes in the cover permit sewer gas to escape. Cable

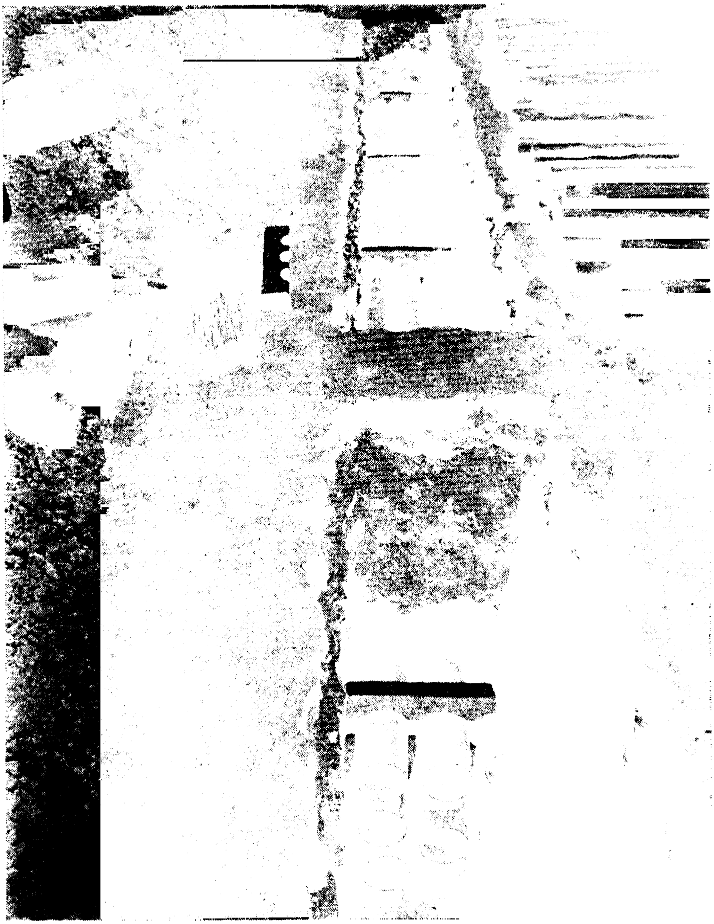


FIG. 636

is drawn into the conduit line after its completion. See Figs. 638, 639, which show the Barnard Clay Products Company's "Hercules Expanding Anchor Bolt." Care must be taken not to puncture the lead sheathing around the cable. Block and tackle or winch mounted on a truck and driven by motor furnish the means for pulling in the cable. One cable is pulled in at a time. The original installation may call for several ducts into which cables are to be drawn as future expansion may demand.

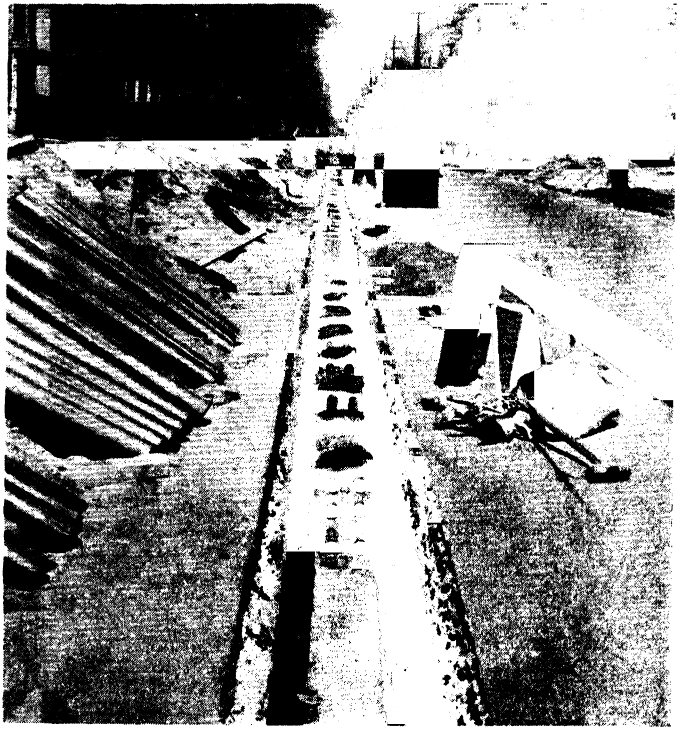


FIG. 637

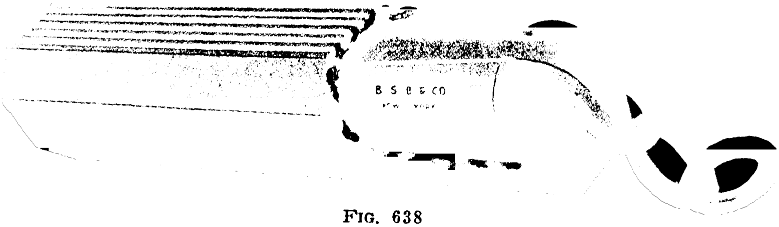


FIG. 638

103. OVERHEAD TRANSMISSION:

Overhead transmission brings with it its own peculiar problems such as "right of way," surface irregularities, stresses and strains due to weight of cable, etc., safety provisions against trespassers, etc.

Cables are supported above ground on poles or towers. Poles are made of wood, concrete, or steel. The wooden pole is far more common than the others, due to its comparatively low cost.

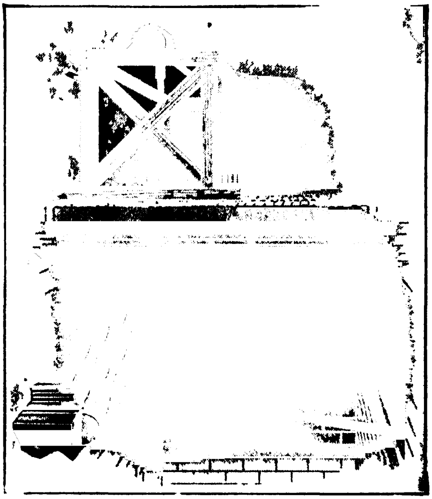


FIG. 639

The problem of preserving the wooden pole after it is placed in the ground is one that has received considerable attention. The common method is to treat the butt end of the pole with creosote. This is sometimes done by soaking for several hours. A better method is to force the creosote into the wood under pressure. Mineral salt treatment is also used by some. It is not common to treat the entire pole.

Concrete poles are sometimes used in place of wooden poles, as for example to support trolley lines. The concrete pole makes a better appearance. It is made of steel-reinforced concrete, the strength depending upon the steel reinforcement. The concrete pole is made with a uniform taper from butt to top. It may be solid or it may be hollow (Fig.

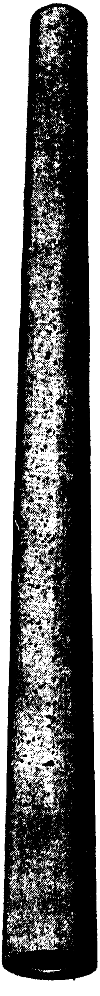


FIG. 640

640), such as the Westinghouse "Hollowspun" pole, this term designating the special spinning process by which it is made. The hollow space may be used for wires as in the case of street-lighting. Provision is also made for fastening cross-arms and other equipment to the concrete-pole, as also for inserting steps to permit easy mounting. The latter are removed after use. The concrete pole needs no preserving treatment.

Steel poles have found favor more recently particularly for high-voltage transmission lines. The common forms are tubular, the latticed steel, and the expanded steel pole. The tubular adapts itself for use in supporting trolley wires and street lamps. The lattice form is square but tapers from base to top. It is fastened to concrete footings and is used for medium range transmission lines (7,500 to 50,000 volts).

The expanded truss steel pole is made from a single piece of steel worked into proper size and shape, without any joints. It serves not only on medium transmission lines, but as a sectional member of a tower.

For heavy duty and for the high-range voltage lines (above 50,000) towers are used almost exclusively. The tower varies considerably in size and shape. Its construction is rigid and permanent in character, capable of supporting heavy load. The legs of the tower are fastened to concrete footings. Distances between towers vary from several hundred to two thousand or more feet, depending upon the load supported and upon the nature of terrain over which the transmission line passes.

104. TRANSMISSION VOLTAGES:

Voltages up to 7,500 are considered low for transmission purposes. The range from 7,500 to 50,000 volts is a medium-voltage range for transmission. Above 50,000 volts is the high-voltage range for transmission.

The transmission voltage determines quite definitely the distance between the wires and also the kind and amount of insulating equipment between wire and support. It is obvious that the pole is limited as to permissible distance between wires and that for the high-voltage range the tower must be used

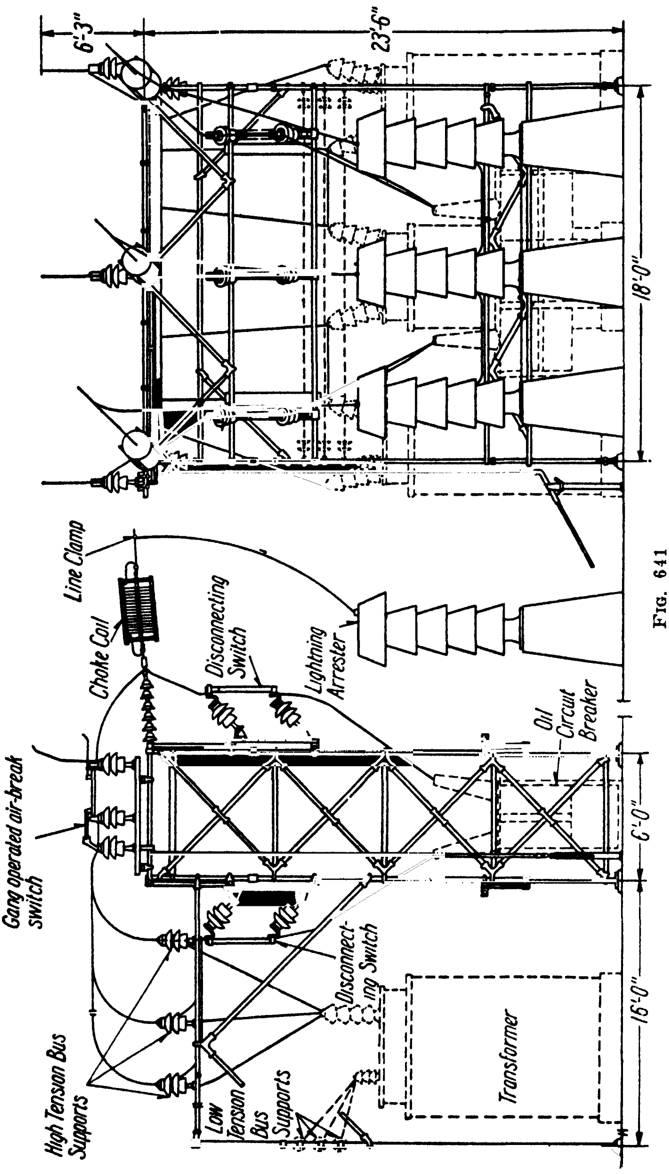

6'-3"
23'-6"
18'-0"
Line Clamp
Choke Coil
Disconnecting Switch
Lightning Arrester
Oil Circuit Breaker
Gang operated air-break switch
6'-0"
High Tension Bus Supports
Low Tension Bus Supports
Disconnecting Switch
Transformer
16'-0"

FIG. 641

Weather conditions of all kinds must be assumed and this adds difficulty to the problem of supporting insulating material that will provide a high factor of safety for the particular voltage transmitted. In the case of the tower, the insulator is suspended from a metal cross-arm. Usually a disk type of insulator is used. Several of these are coupled

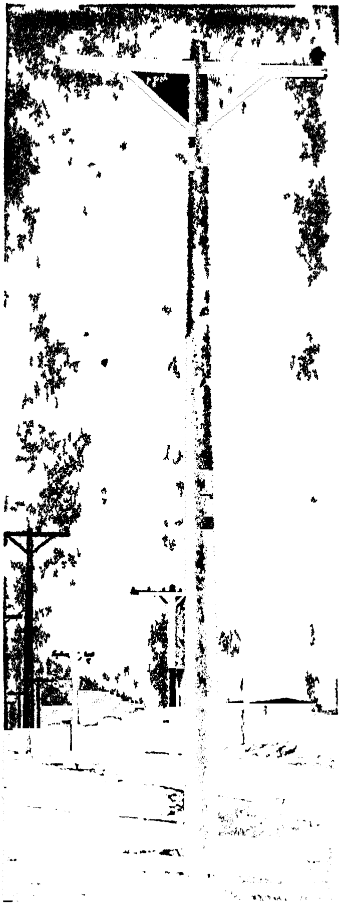


FIG 642

together (series fashion), assuming about 20,000 volts per disk, to give the required protection. The wire is fastened to the lower-most disk by means of a clamp.

To protect conductors against lightning a steel cable is run from tower to tower. This cable is located above the power wires and is supported at the uppermost portion of the tower. Two such steel cables may be used for the same purpose, and then they are fastened to a steel cross-arm above the power cables. The steel cables are thoroughly grounded to permit electrical charges to escape at all times.

High-voltage lines do not pass directly into a building, but rather to step-down transformers located out-of-doors. The reduced voltage is then brought into the sub-station or into the building of the consumer. See Fig. 641.

As already suggested medium and low-voltage transmission lines are frequently supported on poles. See Fig. 642. The wires themselves must be insulated from the supports. The latter are mounted on cross-arms which may be of metal or of wood and which vary in length from 2 to 12 feet.

Insulator pins, of wood or steel, support the insulators themselves. The insulator pin may be fastened by nail or by bolt. Wooden pins may be used only with wooden cross-arms, but metal pins may be used on both the wooden and the metal cross-arm. The free end of the insulating pin is threaded to correspond with inside threads on the insulator itself. The latter is screwed onto the pin, although sometimes insulators are cemented on pins.

Medium-voltage range transmission lines may not enter directly into the sub-station building. They may come to an outdoor transformer sub-station. If brought into an indoor transformer room, special insulators are required to pass through the building walls. These are known as wall bushings and are made of porcelain.

105. SUB-STATIONS:

Sub-stations may be classified as: transformer, motor-generator, rotary converter, or frequency changing stations according to purpose and predominating character of equipment. Many sub-stations combine two or more of these

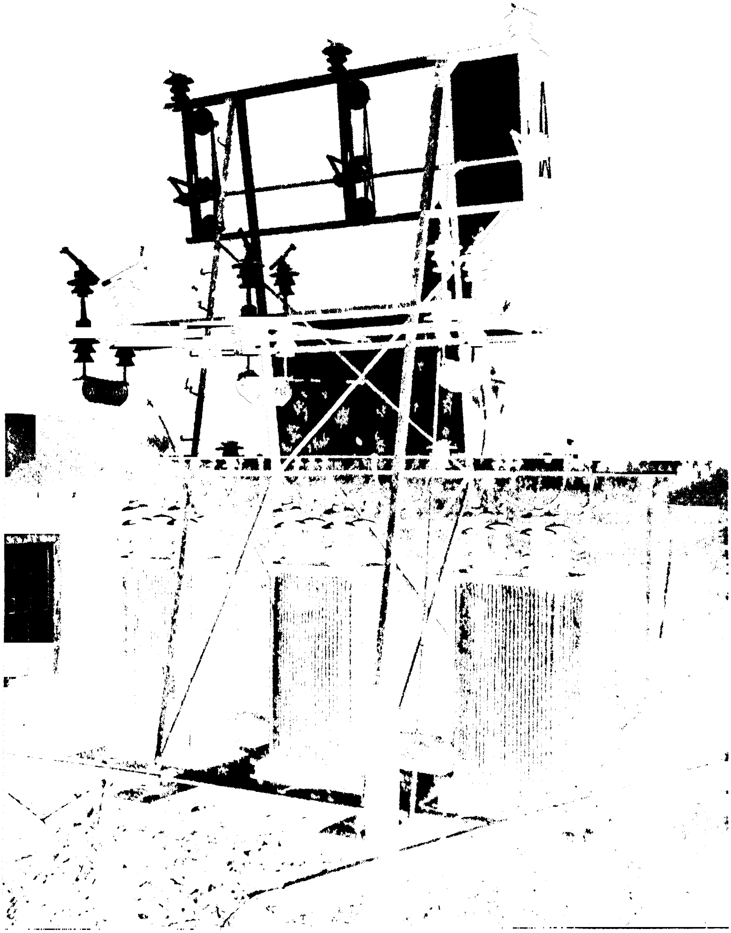


FIG 643

types into a single unit. This is particularly true of the smaller capacity stations.

a) Transformer Sub-stations. Transformer sub-stations may be wholly outdoor, wholly indoor, or partly indoor and partly outdoor. In the last case, only a small building is

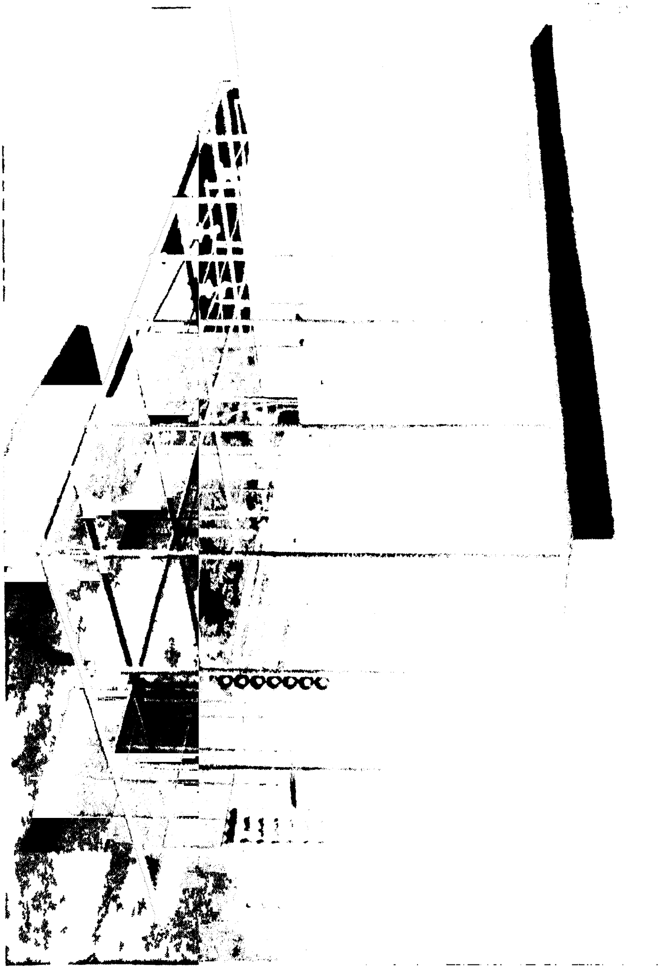


FIG 644

needed to house the necessary switching equipment and auxiliary apparatus.

The transformer sub-station has for its main purpose the stepping-down from high or medium range, to a low-voltage range for distribution to the consumer.

A large installation is shown in Fig. 643 in which three

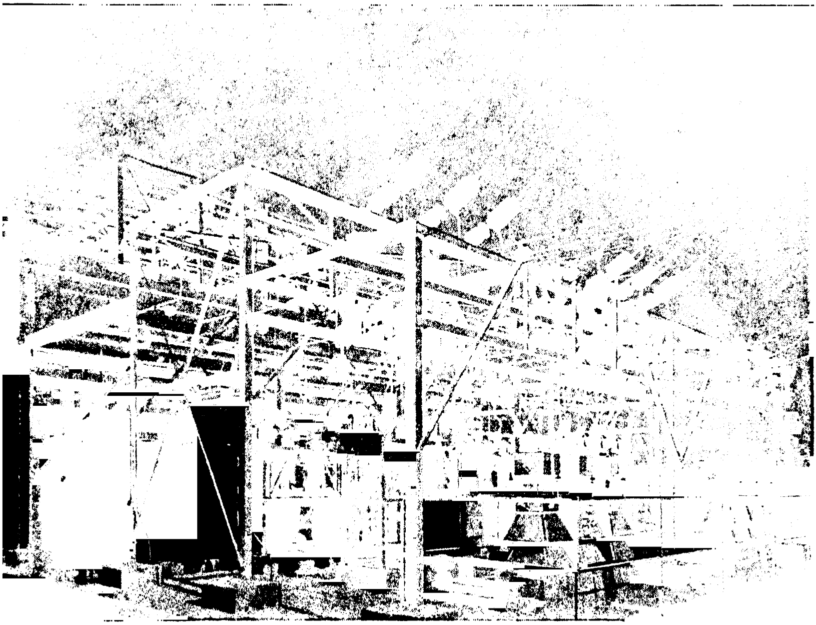


FIG. 645

44,000 volt Kuhlman transformers are pictured with the auxiliary equipment. Fig. 644 illustrates a still larger station. The transformers are "banked." Note the steel framework supporting the lines and insulators, etc.

Figs. 645, 645A show very large sub-stations. The equipment has increased in size, but in general is no different from that in use in the smaller station.

Fig. 646 shows Kuhlman transformers used indoors in a transformer vault. Whether outdoor or indoor, switchboards and switchboard equipment are needed to control the various feeders that branch out to the consumer. Certain equipment such as circuit breakers or oil switches may be housed in separate rooms. Protective equipment such as choke or "reactor" coils, lightning arresters are also needed.

b) Motor-Generator Sub-Station. The transformer station merely changes the voltage. The A.C. voltage (low) may be impressed on an A.C. motor used to drive a D.C. generator or to several such motor-generator sets. Direct current is then distributed to the consumer. Fig. 647 illustrates such a station.

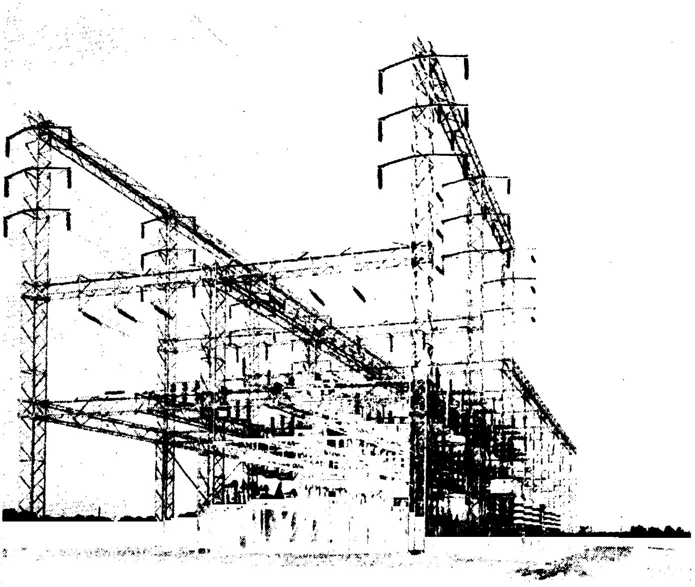


FIG. 645A

c) Rotary Converter Sub-Station. A more common method of changing from A.C. to D.C. is by means of the rotary converter which was described in the previous chapter. A common use is for electric railway service.

d) Frequency Changing Sub-Station. To accommodate requirements in a local area or by an industrial consumer, the A.C. low voltage at 60 cycles may be changed to 25 cycles or less, as well as to 120 cycles or more frequency. This is done by motor-generator sets, the generators being alternators.

FIG. 646

FIG. 647

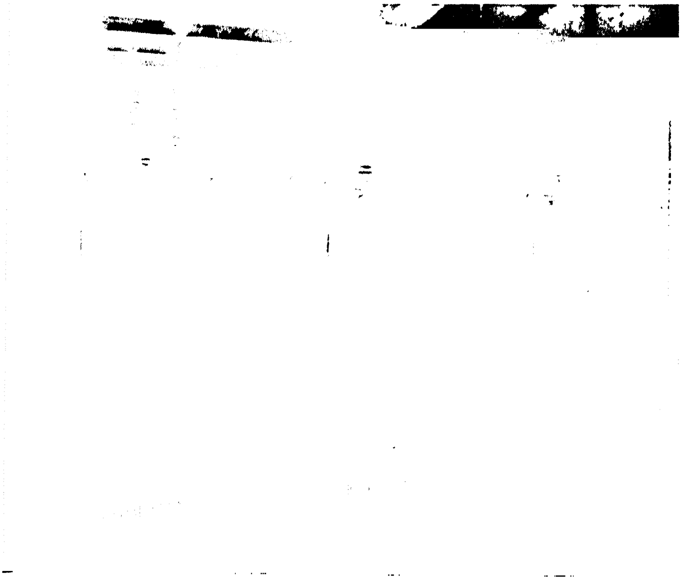


FIG 648

106. CONSUMER VOLTAGES:

Distributing lines carry power to the consumer at many different voltages, although some are more standard than others. Thus D.C. is supplied at 120-240, 440, 550, or 600 volts. A.C. lines to the consumer are below 7,500 volts. Such voltages as 120-240, 2,400-4,800, 6,600 are typical.

FIG 649

Transmission line equipment is much the same on lower-voltage lines, except that it is uniformly smaller. Figs. 648-651 show several installations located either within the consumer's buildings or close by the consumer's buildings, whose purpose is to step voltage down from approximately 6,600 volts to 120-240-440 volts for light and power purposes.

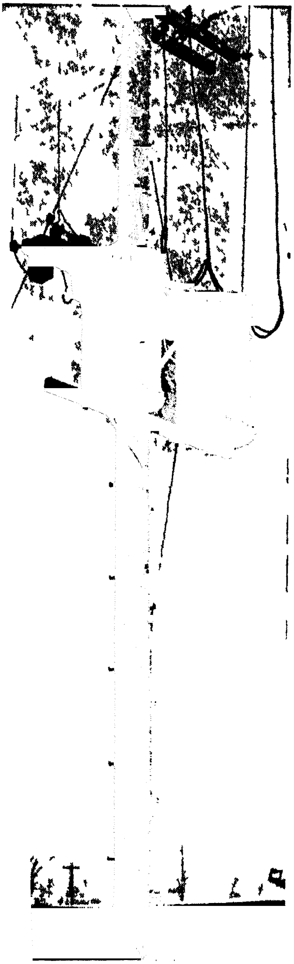


Fig. 650

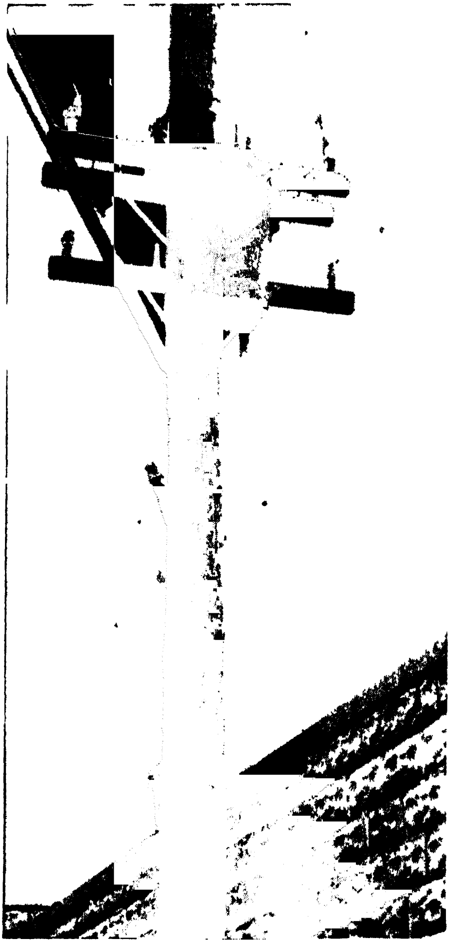


Fig. 651

APPENDIX

TABLE I

Table of Sines and Cosines

Angle	Sin	Cos	Angle
0	.0000	1.0000	90
1	.0175	.9998	89
2	.0349	.9994	88
3	.0523	.9986	87
4	.0698	.9976	86
5	.0872	.9962	85
6	.1045	.9945	84
7	.1219	.9925	83
8	.1392	.9903	82
9	.1564	.9877	81
10	.1736	.9848	80
11	.1908	.9816	79
12	.2079	.9781	78
13	.2250	.9744	77
14	.2419	.9703	76
15	.2588	.9659	75
16	.2756	.9613	74
17	.2924	.9563	73
18	.3090	.9511	72
19	.3256	.9455	71
20	.3420	.9397	70
21	.3584	.9336	69
22	.3746	.9272	68
23	.3907	.9205	67
24	.4067	.9135	66
25	.4226	.9063	65
26	.4384	.8988	64
27	.4540	.8910	63
28	.4695	.8829	62
29	.4848	.8746	61
30	.5000	.8660	60
31	.5150	.8572	59
32	.5299	.8480	58
33	.5446	.8387	57
34	.5592	.8290	56
35	.5736	.8192	55
36	.5878	.8090	54
37	.6018	.7986	53
38	.6157	.7880	52
39	.6293	.7771	51
40	.6428	.7660	50
41	.6561	.7547	49
42	.6691	.7431	48
43	.6820	.7314	47
44	.6947	.7193	46
45	.7071	.7071	45

TABLE II

Single-Phase (Repulsion-Induction Type) Induction Motors

H.P.	Full Load Amperes		Running Fuse Amperes		Starting Fuse Amperes		Size of Wire or Cable	
	115 Volt	230 Volt	115 Volt	230 Volt	115 Volt	230 Volt	115 Volt	230 Volt
½	7	4	10	10	20	10	12	14
1	12	6	15	10	30	20	10	12
2	23	12	30	15	70	30	10	10
3	32	16	40	20	90	30	6	10
5	52	26	65	35	135	60	2	6
7½	77	38	100	50	150	90	0	4
10	98	49	125	65	200	100	00	2
15	141	70	180	90	280	140	200,000	1
20	198	100	250	125	400	200	300,000	0
25		120		150		240		000
30		146		180		300		200,000
40		197		250		400		300,000
50		234		290		470		400,000

TABLE III

Three-Phase Squirrel-Cage Induction Motors

H.P.	Full Load Amperes		Running Fuse Amperes		Starting Fuse Amperes		Size of Wire or Cable	
	220 Volt	440 Volt	220 Volt	440 Volt	220 Volt	440 Volt	220 Volt	440 Volt
1	4	2	10	10	10	10	14	14
2	7	4	10	10	20	15	12	14
3	9	5	15	10	25	15	10	14
5	15	8	20	10	30	15	8	12
7½	22	11	30	15	55	25	6	10
10	25	13	35	20	65	35	6	10
15	38	19	50	25	80	40	4	8
20	51	26	65	35	100	50	2	6
25	64	32	80	40	130	60	1	6
30	77	39	100	50	160	80	0	4
35	92	46	120	60	190	100	0	2
40	107	54	135	70	220	110	00	2
50	118	60	150	80	240	120	000	1
75	178	89	225	115	360	180	0000	00
100	236	118	300	150	470	235	350,000	000
150	355	178	450	225	710	350	500,000	250,000
200	470	235	600	300	940	470	900,000	350,000
250	500	250	740	375	1,180	600	1,200,000	400,000
300	700	350	875	450	1,400	700	1,600,000	600,000

TABLE IV

Three-Phase Wound Rotor Induction Motors

H.P.	Full Load Amps.		Fuse Size Amps.		Size of Wire or Cable	
	220 Volt	440 Volt	220 Volt	440 Volt	220 Volt	440 Volt
5	15	8	20	10	12	14
7½	22	11	30	15	10	12
10	29	15	40	20	8	10
15	41	21	50	25	6	8
20	55	28	70	35	4	6
25	62	31	80	40	2	4
30	81	41	100	50	1	2
35	94	47	125	65	0	1
40	109	55	140	70	00	0
50	127	64	160	80	000	00
75	192	96	240	120	250,000	000
100	248	124	310	160	400,000	200,000
150	366	183	450	225	600,000	250,000

TABLE V

COPPER CONDUCTORS—SOLID

GAUGE A.W.G. (B. & S.) Solid	AREA IN CIRCULAR MILS	SAFE CARRYING CAPACITY, AMPERES		SIZE OF CONDUIT—INCHES					
		RUBBER COVERED	WEATHER PROOF	1 Wire	2 Wires	3 Wires	4 Wires	5 Wires	6 Wires
18	1624	3	5	½	½	½	¾	¾	1
16	2583	6	10	½	½	½	¾	¾	1
14	4107	15	20	½	½	½	¾	¾	1
12	6530	20	25	½	½	¾	¾	¾	1
10	10380	25	30	½	¾	¾	1	1	1
8	16510	35	50	½	¾	1	1	1	1¼
6	26250	50	70	½	1	1¼	1¼	1½	1½
5	33100	55	80	¾	1¼	1¼	1¼	1½	2
4	41740	70	90	¾	1¼	1¼	1½	2	2
3	52640	80	100	¾	1¼	1¼	1½	2	2
2	66370	90	125	¾	1¼	1½	1½	2	2
1	83690	100	150	¾	1½	1½	2	2	2½
0	105500	125	200	1	1½	2	2	2½	2½
00	133100	150	225	1	2	2	2½	2½	3
000	167800	175	275	1	2	2	2½	3	3
0000	211600	225	325	1¼	2	2½	2½	3	3

TABLE VI

Copper Conductors—Stranded

Gauge A.W.G. (B. & S.) Solid	Area in Circular Mils	Stranding	Safe Carrying Capacity, Amperes		Size of Conduit—Inches					
		No. of Wires	Rubber Covered	Weather Proof	1 Wire	2 Wires	3 Wires	4 Wires	5 Wires	6 Wires
6	26300	7	50	70	½	1	1¼	1¼	1½	1½
5	33100	7	55	80	¾	1¼	1¼	1¼	1½	2
4	41700	7	70	90	¾	1¼	1¼	1½	2	2
3	52600	7	80	100	¾	1¼	1¼	1½	2	2
2	66400	7	90	125	¾	1¼	1½	1½	2	2
1	83700	19	100	150	¾	1½	1½	2	2	2½
0	106000	19	125	200	1	1½	2	2	2½	2½
00	133000	19	150	225	1	2	2	2½	2½	3
000	168000	19	175	275	1	2	2	2½	3	3
0000	212000	19	225	325	1¼	2	2½	2½	3	3
....	250000	37	250	350	1¼	2½	2½	3	3	3½
....	300000	37	275	400	1¼	2½	3	3	3½	3½
....	350000	37	300	450	1¼	2½	3	3½	3½	4
....	400000	37	325	500	1¼	3	3	3½	4	4
....	500000	37	400	600	1½	3	3	3½	4	4½
....	600000	61	450	680	2	3	3½	4	4½	5
....	700000	61	500	760	2	3½	3½	4½	....	....
....	800000	61	550	840	2	3½	4	4½	....	....
....	900000	61	600	920	2	3½	4	4½	....	....
....	1000000	61	650	1000	2	4	4	5	....	....
....	1250000	91	730	1150	2½	4½	4½	6	....	....
....	1500000	91	850	1360	2½	4½	5	6	....	....
....	1750000	127	930	1490	3	5	5	6	....	....
....	2000000	127	1050	1670	3	5	6	....	....	....

TABLE VII

Circular Mills and Ampere Carrying Capacity of Flat Bus Bar Copper

Dimensions	Circular Mills	On Basis of 1,000 C.M. per Amp. (in Amps.)	On Basis of 1,200 C.M. per Amp. (in Amps.)	On Basis of 1,600 C.M. per Amp. (in Amps.)
⅛″x1″	159,154	160	133	100
⅛″x1½″	238,731	239	200	180
⅛″x2″	318,309	318	265	200
⅛″x2½″	397,886	398	330	250
⅛″x3″	477,463	477	400	300
⅛″x3½″	557,040	557	464	350
⅛″x4″	636,618	637	531	395
⅛″x5″	795,772	796	663	497
⅛″x6″	954,927	955	800	597
¼″x1″	318,309	318	265	200
¼″x1½″	477,463	477	400	298
¼″x2″	636,618	637	530	398
¼″x2½″	795,772	796	660	495
¼″x3″	954,927	955	800	597
¼″x3½″	1,114,081	1,114	928	696
¼″x4″	1,273,236	1,273	1,060	796
¼″x5″	1,591,545	1,592	1,325	995
¼″x6″	1,909,854	1,910	1,590	1,190
⅜″x1″	477,463	478	400	300
⅜″x1½″	716,194	716	597	448
⅜″x2″	954,927	955	796	597
⅜″x2½″	1,193,658	1,195	995	746
⅜″x3″	1,432,390	1,432	1,195	895
⅜″x3½″	1,671,122	1,671	1,390	1,045
⅜″x4″	1,909,854	1,910	1,590	1,194
⅜″x5″	2,387,317	2,387	1,990	1,490
⅜″x6″	2,864,781	2,865	2,387	1,790
½″x1″	636,618	638	530	400
½″x1½″	954,927	955	796	598
½″x2″	1,273,236	1,273	1,060	796
½″x2½″	1,591,545	1,592	1,326	995
½″x3″	1,909,854	1,910	1,592	1,194
½″x3½″	2,228,163	2,228	1,860	1,393
½″x4″	2,546,472	2,546	2,120	1,592
½″x5″	3,183,090	3,183	2,653	1,989
½″x6″	3,819,708	3,820	3,183	2,380

TABLE VIII

Copper Bus Tubing
(Iron Pipe Size Copper Tubing)

Size of Pipe	Actual C M Area	1,000 C M per Amp (in Amps)	1,200 C M per Amp. (in Amps)	1,500 C M. per Amp (in Amps)	1,600 C.M per Amp (in Amps)
⅛	85,064	85	71	57	53
¼	150,975	151	126	101	94
⅜	221,369	221	184	147	138
½	314,975	315	262	210	196
¾	426,816	427	356	285	267
1	601,381	601	501	401	376
1¼	884,176	884	737	589	553
1½	1,050,000	1,050	875	700	656
2	1,388,781	1,389	1,157	926	868
2½	2,015,625	2,016	1,680	1,344	1,260
3	2,874,156	2,874	2,395	1,916	1,796
3½	3,750,000	3,750	3,125	2,500	2,344
4	4,250,000	4,250	3,542	2,833	2,656

TABLE IX

Copper Rods

Diam in Inches	Area in C.M.	1,000 C.M. per Amp. (in Amps)	1,200 C.M. per Amp. (in Amps)	1,600 C.M. per Amp (in Amps)
¼	62,500	63	52	39
5/16	27,700	98	82	61
⅜	140,600	141	117	88
½	250,000	250	208	156
⅝	390,600	391	326	244
¾	562,500	563	470	350
⅞	765,600	766	640	480
1	1,000,000	1,000	835	630
1⅛	1,265,600	1,266	1,050	790
1¼	1,560,000	1,560	1,300	975
1⅜	1,890,600	1,891	1,580	1,180
1½	2,250,000	2,250	1,875	1,410
1⅝	2,640,600	2,541	2,200	1,650
1¾	3,062,500	3,063	2,550	1,810
1⅞	3,515,600	3,516	2,920	2,200
2	4,000,000	4,000	3,330	2,500

INDEX

INDEX

A

Addition, geometrical............ 20, 47, 57, 61, 74, 75, 100, 101, 113ff., ... 128
Alternator .... 34, 269, 271, 285, 335ff., 338, 339, ...341, 360ff., 414, 415
Ammeter ....136, 149ff.
Ampere 36
Armature reaction ....225, 354ff.
Auto-transformer ....401ff.

B

Back-voltage ..39, 40, 42, 43, 45, 67, 68
Boiler 337, 338
Boiler feed water 337
Brush position 208ff., 265, 294
Brush rigging 217
Brush shift ....212, 213ff.
Brush, short-circuiting 207, 212

C

Capacitance 53
Capacity 47
Cascade ....280, 283ff.
Central Station.........34, 335ff., 378
Characteristics, motor ....218, 220, 221, 229ff., 268, 286ff.
Choke coil 43
Circuits, balanced............... ....109, 125, 126, 129, 130
Circuits, delta.................. 107, 109ff., 252ff., 262ff., 281ff., 393ff.
Circuits, five-wire 101, 102
Circuits, four-phase ...105, 420, 422
Circuits, four-wire 102, 110
Circuits, mesh 103, 107, 110, 111
Circuits, parallel 69
Circuits, polyphase 93ff., 104, 423
Circuits, resonant 74
Circuits, series 69
Circuits, single-phase..93, 104, 105, 109
Circuits, six-phase 395ff., 415
Circuits, star ....103, 106ff., 243ff., 262ff., 393ff.
Circuits three-phase 105, 108ff., 243ff., 252ff., 393ff., 420
Circuits, three-wire 95, 98, 144, 161, 162
Circuits, two-phase 95ff., 105
Circuits, unbalanced ....124ff.
Commutating plane ....208ff.
Compensating winding .218ff., 225, 232
Compensator ..309ff., 316ff., 329, 401
Condenser 48ff., 203ff., 336, 339
Conduit ....426ff.
Converter, rotary.271, 414ff., 440, 444
Cosine 12ff., 17, 18
Cosine table 15, 16, 449
Counter E. M. F..39, 40, 43, 45, 67, 68
Current......................25ff., 35
Current, alternating....27, 31, 33, 35
Current, direct..........33, 35, 37
Current, effective..............37, 38
Current, oscillating............... 27
Current relations...............119ff.
Cycle 30ff., 38

D

Degrees, electrical............... 6
Degrees, mechanical 6
Delta, connection........107, 109, 111
Delta, open 131, 132

E

Efficiency.228, 229, 232, 233, 340, 406ff.

F

Farad 53, 71
Field excitation ....352ff.
Frequency..................31ff., 35
Frequency changer ..280, 440, 444, 445
Frequency meter ....178ff.

G

Graphic meter 140, 141
Graphical solution 18ff., 58
Graphs ....2ff.

H

Half-cycle 31, 60, 79
Henry 48
Hot-wire meter..........136, 155, 156
Hunting 368

I

Impedance 25ff., 56, 57
Impedance triangle 61, 63, 64, 67, 71, 76, 127
In phase 55, 75, 85
Inductance 38, 39, 41, 44
Insulator ....382ff., 437ff.

K

Kilovolt-ampere 86, 87
Kilowatt 86
Kilowatt-hour 86, 159, 340, 341

L

Lag 53, 55, 59, 97, 127, 292, 354ff., 370
Lagging current 53, 54
Lamination 224, 382
Lead 53, 55, 59, 97, 230, 292, 354ff., 370
Leading current...............53, 54
Lines of force..................39, 41, 43, 188, 189, 272ff., 354ff., 372

M

Magnetic effect 39, 40
Magnetic field 39, 40, 342
Magnetic whirls 39, 40
Meter, frequency ....178ff.
Meter, hot-wire 136, 155, 156
Meter, thermal ....156ff.
Meter, power factor ....173ff.
Meters ....136ff.
Microfarad 53, 71
Millihenry 43, 44
Motor, condenser ....203ff.
Motor, Fynn-Weichsel ....292ff.
Motor, induction 185ff., 239, 280, 283, 288ff., 295, 450, 451
Motor, repulsion 186, 206ff., 222, 223, 230
Motor; repulsion-induction..............186, 220, 221, 223, 231ff., 450
Motor, repulsion starting.....221, 222
Motor, series ....186, 223ff., 233ff.
Motor, shaded pole 186, 187
Motor, single-phase 185ff., 229, 298, 450
Motor, split-phase 186, 191ff., 206, 207, 229
Motor, synchronous 239, 268ff., 276, 286ff., 291, 292, 295, 369, 370, 415
Motor, three-phase 239ff., 450
Motor, universal ....224ff., 233ff.
Motor, variable speed 217, 218, 231, 232, 266, 280, 283, 284, 322
Motor, wound rotor...............................239, 261ff., 280, 283, 284, 290, 291, 295, 323, 324, 451
Motor starters, manual.....................298ff., 303ff., 309ff., 322ff.
Motor starters, magnetic ....324ff.

N

Neutral line.101, 103, 104, 109, 110, 116
Neutral plane ....208ff.
No-voltage protection 316

O

Ohm 36
Ohm's law 40, 66, 69
Open delta 131, 132
Out of phase 55, 98
Overload protection.......................308, 313ff., 321, 322, 329ff.

P

Parallel operation ....360ff.
Phase 54, 55
Phase angle 70, 73, 75, 83, 85
Phase rotation 107, 368
Pole ....435ff.
Power .... 77ff.
Power, apparent 88, 89
Power, real................83, 88, 89
Power, three-phase ....129ff.
Power factor.......................84ff., 129ff., 229, 230, 233, 292, 340
Power factor meter ....173ff.
Primary coil 210, 317, 373, 401
Proportion 11, 12
Pyrometer ....180ff.

R

Ratio 11, 12
Reactance ....38, 39, 45, 52, 56ff.
Reactance Capacity...............................47, 52, 53, 56, 57, 59
Reactance, inductive 44, 52, 53, 56, 57, 59, 68
Reactor 43
Reconnecting 280, 281
Recording meter 140, 141
Resistance.................34, 38, 45
Resistance, effective 35
Resonance 74
Reversing rotation.........197ff., 216
Revolving field ....196, 271ff.

Rotor, squirrel cage ....
187ff., 202, 204, 206, 239, 256, 259, 261
Rotor, wound .....192, 209, 210, 261ff.

S

Scott connection ....397ff.
Secondary coil 210, 317, 373, 401
Shaded pole 186ff., 195
Shading coil 187, 188, 195
Sine 12ff., 17
Sine table 15, 16, 449
Skin effect 34, 35
Slip 226, 227, 278ff., 283, 284, 423
Slip rings 94, 96, 106, 263, 264, 270
Speed, synchronous ....
......226, 227, 230, 279, 280, 286, 423
Split-phase ...186, 191ff., 206, 207, 229
Squirrel cage...................
.......................187ff., 202,
204, 220, 222, 239, 256, 259, 261
Starters, motor ....
..........298ff., 303ff., 309ff., 322ff.
Static electricity ....48ff.
Stator ....191, 192, 206, 223, 239ff.
Sub-station ....339, 378, 440ff.
Superheating 338
Switch, centrifugal 193ff., 198, 222
Switch, oil 307, 308, 443
Switch, short circuiting..222, 263, 267
Switch, star-delta..............309ff.
Synchronizing 171, 172, 362ff., 423
Synchronizing lamps...........365ff.
Synchroscope ....171ff., 365ff.

T

Thermal meter ....156ff.
Torque ....189, 211, 215, 228ff.
Transformer ....
.............94, 277, 278 316ff., 329
334, 339, 372ff., 426, 440, 443, 444
Transformer current 167, 168, 170
Transformer, instrument ....165ff.
Transformer, potential..166, 169, 170
Transformer, special duty......408ff.
Transformer connection.........389ff.
Transformer cooling............384ff.
Transformer polarity...........387ff.
Transmission ......337, 339, 373, 425ff.
Turbo-alternator.34, 336, 338, 339, 360

U

Under-voltage protection.....313, 314

V

Vectors ....
18ff., 57ff., 62, 66, 69, 71, 74, 88,
100, 101, 113ff., 128, 197, 345ff.,
358, 359, 362, 399, 400, 404ff.
Vee connection 132
Volt 36
Volt-ampere 87
Voltage, alternating............ 25ff.
Voltage, average 37, 38
Voltage, consumer 447
Voltage, effective 37, 38
Voltage, instantaneous 37, 38, 78
Voltage, maximum..............
............28, 29, 37, 38, 51, 52, 78
Voltage regulation.......354ff., 403ff.
Voltage regulator.....356, 357, 412ff.
Voltage relations...............112ff.
Voltage transmission ....437ff.
Voltmeter ....149ff.

W

Wattmeter ....82, 131, 143ff.
Wattmeter, polyphase 146
Watt-hour meter ....158ff.
Watt-hour meter, demand..164, 165
Watt-hour meter, pre-payment ..
..........................164, 165
Wave shape 342, 343
Winding......242, 243, 245ff., 280, 342
Winding, compensating 218ff., 221, 230
Winding, running ....
..........192ff., 203ff., 219, 220, 293
Winding, starting..............
..........192ff., 203ff., 219, 220, 293

Y

Y-connection 106, 107, 109

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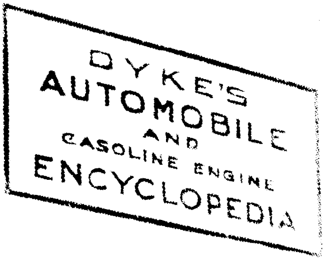

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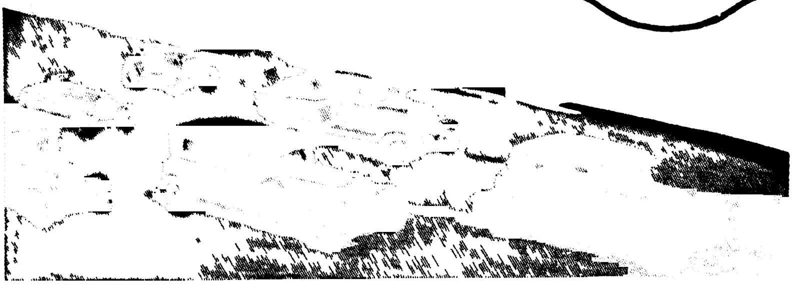

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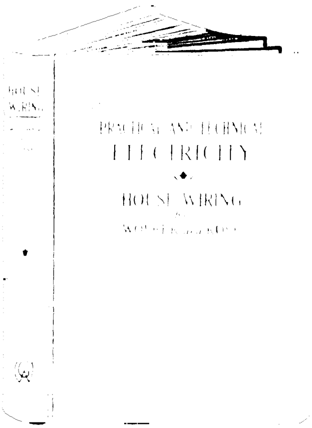

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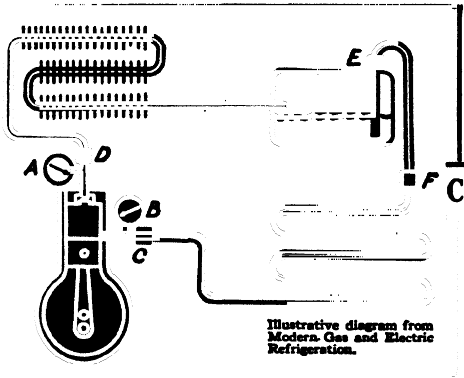

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